Cooling of Quark Stars in the Color Superconductive Phase: Effect of Photons from Glueball decay

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ABSTRACT

The cooling history of a quark star in the color superconductive phase is investigated. Here we specifically focus on the 2-flavour color (2SC) phase where novel process of photon generation via glueball (GLB) decay have been already investigated (Ouyed & Sannino 2001). The picture we present here can in principle be generalized to quark stars entering a superconductive phase where similar photon generation mechanisms are at play. As much as $10^{45} - 10^{47}$ erg of energy is provided by the GLB decay in the 2SC phase. The generated photons slowly diffuse out of the quark star keeping it hot and radiating as a black-body (with possibly a Wien spectrum in gamma-rays) for millions of years. We discuss hot radio-quiet isolated neutron stars in our picture (such as RX J185635-3754 and RX J0720.4-3125) and argue that their nearby blackbody spectra (with a few broad features) and their remarkably tiny hydrogen atmosphere are indications that these might be quark stars in the color superconductive phase where some sort of photon generation mechanism (reminiscent of the GLB decay) has taken place. Fits to observed data of cooling compact stars favor models with superconductive gaps of $\Delta_{2SC} \sim 15-35$ MeV and densities $\rho_{2SC} = (2.5-3.0) \times \rho_N$ ($\rho_N$ being the nuclear matter saturation density) for quark matter in the 2SC phase. If correct, our model combined with more observations of isolated compact stars could provide vital information to studies of quark matter and its exotic phases.

Key words: dense matter – stars: interior

1 INTRODUCTION

Quark matter at very high density is expected to behave as a color superconductor (e.g. Rajagopal & Wilczek 2001). Of interest to the present work is the 2-flavor color superconductive phase, the 2SC phase, where only the up and down quarks of two color (say, $u_1, u_2, d_1,$ and $d_2$) are paired in a single condensate, while the ones of the third color (say, $u_3$ and $d_3$) and the strange quarks of all three colors are unpaired. Associated with superconductivity is the so-called gap energy $\Delta_{2SC}$ inducing the quark-quark pairing and the critical temperature ($T_c$) above which thermal fluctuations will wash out the superconductive state.

The cooling of quark stars in such a phase\textsuperscript{1} has previously been investigated in the literature. It was found that a crust must be included for 2SC star cooling to be compatible with existing data (Blaschke et al. 2000). As for the cooling of hybrid stars (neutron stars with a 2SC core), it is believed that small gaps ($\Delta_{2SC} < 1$ MeV) tend to reproduce cooling curves which agree well with the observed data (we refer the interested reader to §6 in Weber 2005 and references therein). Whether such small gaps can be justified and why the crust - believed to be tiny in quark stars - is so crucial to cooling is debatable. More recent studies of these hybrid stars find that unless all quarks are gaped the stars cool too fast in disagreement with observational data (the fast cooling is due to direct Urca process on unpaired quarks; we refer the reader to Blaschke et al. 2005 for more details). However the studies mentioned above did not include internal heating mechanisms as we do here (the GLB decay) which as we will show have definite consequences on the cooling history and spectral features of these stars. Furthermore, there are still pulsar candidates these models fail to explain leaving room for exploring other possibilities.

A novel feature of the 2SC phase is the generation of GLB particles (hadrons made of gluons) which as demonstrated in Ouyed & Sannino (2001) immediately decay into photons. These GLBs appear at temperatures much below the critical temperature for the onset of the superconductive phase. We isolate three cooling steps: (i) in the early hot stages when the quarks are still unpaired the neutrino emission is due to the three quark direct Urca processes

\textsuperscript{1} Here we only consider the stars in 2SC phase. Cooling of quark stars in the Color-Flavor-Locked phase where strange quark enters the dynamics, has also been investigated in the literature and it was shown they cool down too rapidly in disagreement with observations (e.g., Schaab et al. 1997; Blaschke et al. 2001).
$u_c + e^- \rightarrow d_c + \nu_e$ and $d_c \rightarrow u_c + e^- + \bar{\nu}_e$, where the subscript $c$ denotes the quark color. The star rapidly cools to $T_c$ thus entering the 2SC phase; (ii) in the 2SC phase the paired up and down quarks of two colors do not contribute to cooling thus reducing neutrino emission (see Page & Uslov 2002 for more details). While reduced by a factor of 3, the neutrino emission remains the dominant cooling mechanism until the star has cooled to the critical temperature for GLB formation; (iii) at this point in time, the GLBs decay to photons providing an extra heat source and the cooling becomes driven by these photons slowly escaping from the star. We should note that this photon cooling stage might be particularly dominant for the further cooling history of the star for cases and situations where neutrino cooling is quenched (e.g., by secondary pairing of the $u_3$ and $d_3$ quarks as discussed in Page & Uslov 2002). This third phase, unique to our model, alters the cooling history of the star keeping hot and radiating as a blackbody for millions of years as we show in this work.

1.1 Caveats on the 2SC phase and model generalities

It has been argued that once the conditions of charge neutrality and $\beta$-equilibrium are enforced it appears that the so-called “gapless 2SC phase”, or g2SC, might be the favoured ground state (Shovkovy & Huang 2003; Aguilera et al. 1995). Other studies instead favor the so-called “gapless CFL phase”, or gCFL (Alford, Kouvias, & Rajagopal 2004; and references therein). These alternatives (g2SC and gCFL) however might be prone to instabilities begging for serious scrutiny before this debate can be settled (e.g. Shovkovy, Rüster, & Rischke 2004; Huang & Shovkovy 2004; He et al. 2005). The differences in these studies are connected with the choice of the model parameters and is beyond the scope of this paper. For g-2SC the most likely matter of the instability is a transition to a crystalline superconductor (e.g. Casalbuoni et al. 2005)$^2$. If such a transition occurs on much longer timescales than GLB formation and decay time (i.e. $10^{-13}$-$10^{-14}$ s; Ouyed & Sannino 2001) then our model should still be valid: a stable 2SC/g-2SC phase is not a necessary condition. As we have said, the picture we are presenting here in its generality should apply to quark stars in any phase where photon generation mechanisms are at play (e.g. Vogt, Rapp, & Ouyed 2004).

The paper is presented as follows: In Sect. 2 we briefly present the GLB formation and decay in the 2SC phase followed in Sect. 3 by a description of the model’s assumption. Cooling calculation results are shown in Sect. 4 with a comparison to observed data. In particular, radio-quiet isolated neutron stars are discussed in the context of our model in Sect. 5. We conclude in Sect. 6.

2 GLUEBALL FORMATION AND DECAY

The GLB mass is given in Ouyed & Sannino (2001) as,

$$M_{GLB}^2 = \frac{\sqrt{6}}{2\sqrt{\pi}} \hat{\Lambda}^2. \tag{1}$$

Figure 1. Glueball mass (solid) and deconfinement temperature (dotted) vs chemical potential for two different QCD energy scales, $\Lambda_{QCD} = 150$ MeV (top panel) and $\Lambda_{QCD} = 300$ MeV (lower panel).

$$b = 22/3, c^2/4\pi = 1/137 \text{ and } d \text{ is a positive constant of order unity, and}$$

$$\hat{\Lambda} \simeq \Delta \exp \left( \frac{2\sqrt{2}\pi}{11} \frac{\mu}{g(\mu)\Delta} \right). \tag{2}$$

In the expression above, $\mu \propto \rho^{1/3}$ is the chemical potential ($\rho$ is the quark matter density) and $g(\mu)$ the effective energy dependent coupling constant defined as $g(\mu)^2/4\pi \simeq 1/\ln(E/\Lambda_{QCD})$ where $\Lambda_{QCD}$ is the QCD energy scale. Here $E$ is the energy scale at which the theory is being applied which in our case is $E \sim \mu$.

It has been shown in Sannino et al. (2002) that the GLBs appear (or enter the dynamics) at the critical temperature,

$$T_{GLB} = \frac{\alpha(\Lambda)\pi v}{4\sqrt{2}\pi^2 \hat{\Lambda}}, \tag{3}$$

(for $T > T_{GLB}$, GLBs “melt”) where $v = 1/\sqrt{\lambda}$ is the gluon velocity with the dielectric constant ($\epsilon$) and the magnetic permeability ($\lambda$) given as (Rischke et al. 2001)

$$\epsilon = 1 + \frac{g(\mu)^2\mu^2}{18\pi\Delta^2}, \quad \lambda = 1 \tag{4}\text{.}$$

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Figure 1 shows the mass, $M_{GLB}$, and $T_{GLB}$ of the GLBs for different gaps and chemical potentials for the two cases of $\Lambda_{QCD} = 150$ MeV and 300 MeV. For the quark matter densities considered here and a gap of tens of MeV the GLBs mass is of the order of a few MeV. We also note that in general $T_{GLB} \approx M_{GLB}$. In the following we define $E_\gamma$ as the photon energy from the GLB $\rightarrow \gamma\gamma$ reaction.

3 SCENARIO DESCRIPTION AND ASSUMPTIONS

We begin with a hot quark star in the quark-gluon plasma phase cooling and undergoing the transition into the 2SC phase. As mentioned in the introduction, neutrino cooling will be dominant at first
and the star rapidly reaches the temperature $T_c \sim 0.57\Delta_{2SC}$ for the onset of the 2SC phase. The neutrino cooling is also dominant in the 2SC phase despite a decrease in neutrino emission induced by pairing of quarks (Carter&Reddy 2000; Page&Usov 2002) until ultimately the star cools to $T_{GLB}$ at which point in time the GLBs start forming. We assume for simplicity that the entire star cools to $T_{GLB}$ and any temperature gradients in the early stages will be smoothed out; which is not unreasonable given the extremely large conductivity of the 2SC phase (e.g. Heiselberg&Pethick 1993). All of the GLBs immediately decay into photons and beyond this stage cooling is dominated by the photons which slowly diffuse out of the star.

3.1 Total photon energy and plasma cut-off

It was shown that 3/8 of the total number of gluons will form GLBs (Ouyed & Sannino, 2001). This implies that 3/8 of the nucleon binding energy, 938 MeV, is transformed to GLBs which amounts to roughly 350 MeV in photon energy per nucleon. For a 10 km radius quark star and matter densities on the order of $\rho_{\text{SN}}$ ($\mu \sim 350$ MeV) this translates to a total energy $E_{\gamma,\text{tot}} \approx 10^{53}$ ergs released as photons; $\rho_{\text{SN}} = 2.71 \times 10^{14}$ g cm$^{-3}$ is the nuclear matter saturation density. However, let us recall that the emissivity of photons at energies below that of the plasma frequency ($E_{\gamma} = \hbar\omega_{\text{p}} \approx 20\text{-}25$ MeV for the density regime representative of 2SC phase) is strongly suppressed (Alcock, Farhi, & Olinto 1986; Chmaj, Haensel, & Sominin 1991; Usom 2001). As such, only the tail ($E_{\gamma} > 20\text{-}25$ MeV) of the distribution will exist inside the 2SC star. The true available total energy in photons is then $E_{\gamma,t} \approx \int^{\infty}_{0} f_\gamma dE_{\gamma} = E_{\gamma,\text{tot}} \approx (10^{-6}$ \text{-} $10^{-8}) \times E_{\gamma,\text{tot}} \approx (10^{45}$\text{-}10$^{47}$) ergs; here $f_\gamma$ is the Planck distribution; we note that different distributions lead to same values for $E_{\gamma,t}$ but as we state in §4.1 these photons will eventually acquire a Wien distribution as they leak out of the star.

4 COOLING AND LIGHTCURVES

For the range in temperature, $T$, considered here the vast majority of quarks in the star are in their ground states $kT/\hbar\nu << 1$ where $\hbar\nu$ is the Fermi energy. The density of the free quarks at temperature $T$ that will interact with the photons is

$$N_q = \frac{\pi}{3} \left[ \frac{2\epsilon m_q k_B T}{\pi^2 \hbar^2} \right]^{\frac{2}{3}},$$

(5)

where $\epsilon$ is the electronic charge and $m_q$ is the quark mass.

The problem we are solving here is that of a uniform sphere of constant density and constant temperature gas of fermions and a homogeneous source of photons with $E_{\gamma} > kT_q$ where $T_q$ is the temperature of the quarks in this case. The number of photons escaping as a function of time we calculated using the numerical method described by Sunyaev&Titarchuk (1980, hereafter ST80; see also Shapiro et al. 1976 and Miyamoto 1978). The corresponding diffusion equation in spherical coordinates is

$$\frac{\partial J}{\partial \tau} = \frac{1}{3\tau^2} \frac{\partial}{\partial \tau} \left( \frac{\tau^2 \partial J}{\partial \tau} \right),$$

(6)

where $J$ is the average intensity of emission and is a dimensionless quantity (following ST80 choice of units), $u$ is the dimensionless time ($u = \sigma N_q t$; $c$ is the speed of light, $t$ is the time in seconds, and $\sigma = \pi \lambda_q^2$ where $\lambda_q = \frac{\pi (2\pi \hbar c / (k_B T)^2 + m_q^2 c^4)}{1}$ $\approx 1$ fm$^{-1}$; the cross-section $\sigma = \pi \lambda_q^2$ is introduced to make use of dimensionless description as explained in ST80 following Chapline & Stevens (1973). We should note however that a complete mechanical prescription (using relativistic Compton cross-section in the appropriate regime where $\hbar \nu > kT_q$) was used in deriving equation 6. More specifically the treatment of cross-section we adopted is that of Miyamoto (1978) which is consistent with the use of the Compton Focker-Planck equation.

Figure 2 shows the cumulative percentage of the total energy that has escaped from the surface of a 10 km radius quark star is plotted for increasing time. The amount of escaped energy is shown as a percentage of the initial energy contained within the quark star at $t = 0$; the curves from left ($T_{GLB} = 1$ MeV) to right ($T_{GLB} = 10$ MeV) are in 1 MeV step.

is the quark wavelength$^3$, and $\tau$ is the dimensionless optical distance from the center of the star ($\tau = \sigma N_q R_q$ where $\tau$ is the distance from the center of the star). To find the escape time distribution function $P(u)$ of a single photon we have to normalize the function obtained $J(\tau_0, u)$ (see Appendix A in ST80 for details) so that

$$\int_{\tau_0}^{\infty} P(u)du = 1,$$

and

$$P(u) = \frac{J(\tau_0, u)}{\int_{\tau_0}^{\infty} J(\tau_0, u)du} = \frac{1}{\tau_0} \left( \frac{\pi u}{3} \right)^{\frac{3}{2}} \exp \left( \frac{\pi^2 u}{3\tau_0^2} \right),$$

(7)

where $\tau_0 = \sigma N_q R_q$ is estimated at surface of the star of radius $R_q$. Equation (7) gives the normalized probability of escape for photons from the surface of the star as a function of time. We then adjust the magnitude of the distribution so that its area is equal to the total number of photons, with $E_{\gamma} > \hbar\nu$, from GLB decay. The total number of photons escaping versus time was then converted to luminosity and to surface temperature, $T_s$, using the black-body formulation (see below).

Figure 2 shows the cumulative percentage of the total energy generated through GLB decay that has been radiated from the surface of 10 km radius star as a function of time. It takes at least $5 \times 10^7$ years for the energy to escape the dense quark star and
so we conclude that GLB decay in quark stars does not constitute a suitable inner engine for gamma ray bursts (GRBs) as originally claimed in Ouyed&Sannino (2002); recent work by Ouyed et al. (2005) suggests instead that quark stars in the CFL phase constitute better candidates for GRB inner engines. However, Fig. 2 and Fig. 3 show that if GLB decay does occur in a quark star the object will be extremely bright and should be readily observable.

4.1 The escaping photons: A Wien spectrum

In its simplest approach the quark-photon interaction can be described using elementary random-walk theory which tells us that the average number of quark scatterings will be approximately equal to $\tau_s^2$, with $\tau_s = R/\lambda_\nu$ and $\lambda_\nu \simeq 1$ fm being the Compton mean-free path of the photons. Furthermore, the average fractional energy transfer in a quark-photon scattering will be of the order of $(2kT_q/m_\gamma c^2)$. For $\tau_s >> 1$, as is in our case, one can show that the initial photon spectrum is distorted into a distribution having approximately the shape of a Wien spectrum (e.g., Chapline & Stevens 1973). In general, it is found that an equilibrium solution to the Compton Fokker-Planck equation is a Bose-Einstein distribution which, for $h\nu > kT_q$ and large $\tau_s$, approaches a Wien spectrum (Miyamoto 1976 and references therein). That is, the time the photon escape the star their distribution will be given by $F_\nu \propto \nu^3 \exp(-\nu/kT)$. 

4.2 Thermalization: A black-body spectrum

A property of quark stars is the existence of an “electrosphere” extending a few hundred to a thousand Fermi above the surface of the star (see Usov, Harko & Cheng for a recent study). Based on a collisional treatment of photons on single electrons and given the electron density in the electrosphere, $n_e \sim 10^{-5} - 10^{-4}$ fm$^{-3}$, one can show that photons with energies $E_\gamma \gtrsim 10^5$ MeV will not be affected by the layer (Cheng & Harko 2003; Jaikumar et al. 2004). In other words, the escaping photons do not scatter often in the electrosphere to become thermalized.

However, the outflowing high energy ($E_\gamma \gg m_e c^2$) photons enter a region rich in $(e^+e^-)$ pairs and low energy $(<< E_\gamma)$ photons (Aksenov et al. 2004). The corresponding ‘compactness parameter’ $l = L/\sigma T/4\pi R c^2 >> 1$ (e.g. Frank, King, & Raine 1992) implies ideal conditions for $\gamma \gamma \rightarrow e^+e^-$ processes to take place quickly leading to thermal equilibrium (e.g. Paczyński 1990). We thus expect the Wien distribution of the escaping photons to evolve into a black-body although a residual Wien tail in gamma-rays ($\gtrsim 20-25$ MeV) could survive as a signature of the original distribution.

4.3 Crust effects

The electrosphere allow for radial electric fields whose magnitude can support matter against the star’s gravity. The mass of the crust which can exist suspended by this electric field cannot exceed $10^{-5} M_\odot$ (Alcock et al. 1986; Horvath et al. 1991). Its effect can be quantified by relating the “internal” temperature $T_i$ or the temperature at the bottom of the crust to the effective temperature at the surface of the crust via the so-called Tsuruta law (Tsuruta 1979). The formula for thick crusts is (see also Shapiro&Teukolsky 1983, p330) $T_\infty = (10T_i)^{2/3}$. We note however that for quark stars the crust is much thinner than in the NSs. Therefore, we will investigate the two extreme cases of negligible or no crust ($T_\infty \simeq T_i$; e.g. Pizzochero 1991) and thick or maximum crust ($M_{\text{max}} \simeq 10^{-5} M_\odot$) using the Tsuruta formula. In both cases, the effective temperature as seen by a distant observer is $T_\infty = T_i \sqrt{1 - R_{\text{Sch}}/R}$ where $R_{\text{Sch}}$, is the star’s Schwarzschild radius.

4.4 Comparison to observations

The related cooling curves are shown in Figure 4 for different initial temperatures $T_0$ and for a star of radius $10$ km. Models with maximum crusts do not appear to be successful when compared to cooling of neutron stars if these are quark stars. The corresponding cooling curves start overlapping with observed data for $T_{\text{GLB}} > 0.57 \Delta_{\text{2SC}}$ which is outside the 2SC phase where GLBs cannot form. Such temperatures will not be sustained since we expect neutrinos will drive $T_{\text{GLB}}$ to lower values early in the star’s cooling history. When compared to observed data our cooling curves agree best with models of stars with thin or no crusts and for temperatures $0.8 < T_{\text{GLB}} < 2$ MeV. The regime favored by the best fits correspond to densities $\rho_{\text{2SC}} = (2.5-3.0) \times 10^{17}$ (or $\mu = 350-450$ MeV) and energy gaps $\Delta_{\text{2SC}} = 15-30$ MeV (§2). In general, in our model best fits to observations favor quark stars with thin or no crusts. This is also consistent with the fact that quark stars are expected to be born bare given the extreme temperatures involved during their formation. In the so-called ‘Quark-Novae’ scenario (Ouyed et al. 2002; Keränen et al. 2005) for example the crust could be regenerated from fall-back material but it is expected to be thin. This brings to the special family of hot radio-quiet isolated neutron stars (INSs) within the picture we presented so far. Specifics below.

5 RADIO-QUIET ISOLATED NEUTRON STARS

5.1 Observations

There are about 7 radio-quiet isolated neutron stars (INSs) that show features that might be of interest to us. There are important clues from observations that are worth mentioning: (i) While recent XMM-Newton observations of 4 radio-quiet INSs show clear features (in particular RX J0720.4-3125 show a clear broad feature at around 310 eV; Haberl et al. 2004), RX J1856.5-3754 remains featureless; (ii) it is believed that the observed broad features are absorption due to the proton cyclotron line. These hydrogen lines it was suggested could arise from a pure hydrogen atmosphere (van Kerkwijk et al. 2004); (iii) what is further remarkable about these objects is the optical excess observed in their spectra as compared to the X-ray component (e.g. kaplan et al. 2003). Recent studies of this phenomenon show that a thin (1 cm thin and not exceeding $10^{14}$ g) layer of hydrogen atmosphere can well represent both the optical and X-ray data without invoking additional thermal component (Mocht et al. 2003); (iv) finally, there are indications that accretion might not be important since the rates must be many orders of magnitudes smaller than the Bondi-Hoyle rates of $\sim 10^{8}$ g/s (Bondi & Hoyle 1944; Bondi 1952). Mocht et al. (2003) estimate from fits to optical emission that the total mass of hydrogen is no more than $2 \times 10^{12}$ g which translates into accretion rates not exceeding 1 g/s. A second clue that accretion might not be at play
in these sources is the $H_\alpha$ nebula surrounding $RX\, J1856.5-3754$ which can be attributed to a relativistic wind (van Kerkwijk & Kulkarni 2001).

5.2 Our scenario

The newly born bare quark star could regain its crust by accretion from the ISM or from fall-back material during its formation (Keraän et al. 2005). In both of these possibilities a tiny hydrogen envelope can only be explained if accretion rates are less than 1 g/s. Such rates are puzzling and difficult to account for and we would rather assume that accretion is irrelevant (see point (iii) in §5.1) and that the star regained a crust from fall-back material as in the case of the 'Quark-Nova' scenario (Ouyed et al. 2002; Keraän et al. 2005) or any similar formation scenarios of quark stars. We should however mention the scenario discussed in Usov (1997) where it is argued that in the case of more or less spherical (Bondi) accretion onto a nearly bare quark star only a small part of falling gas is collected at the stellar surface. The bulk of this gas passes through the quark surface leaving a rather low-mass steady hydrogen atmosphere ($\sim 10^{12}$ g). Below we discuss another possibility whereas...
the original crust is slowly depleted in time that might possibly explain the clustering in time and temperature of INSs.

An important intrinsic property of quark stars is the dependency of the size of the crust on the properties of the electrosphere (Alcock et al. 1986; Usov et al. 2005) which in turn are very sensitive to the global charge neutrality of the star and its temperature. While in the case of pure CFL it has been argued in the literature that in such a state the star is globally neutral by construction (Rajagopal & Wilczek 2001; see however Usov 2005) we ask ourselves the question of what happens in the case of 2SC, g2SC and gCFL? As these stars cool one could imagine that they slowly evolve to a more globally neutral configuration. Presumably the electrosphere and the corresponding electric field are reduced in time which would correspond to the crust shrinking to eventually reach infinitesimal size when most of the electron in the electrosphere have been reabsorbed by the quark matter. What is interesting in this scenario we suggest - which remains to be confirmed - is the fact that the bottom of the crust (dominated by the settled heavy elements) sinks closer to the quark matter surface. Over time the crust material is slowly depleted/deconfined from the bottom leaving the lighter upper atmosphere material.

In our scenario then the smaller the crust gets as the star cools and reduces its electrosphere the richer in lighter elements (and ultimately in hydrogen) it becomes. The end result we suggest is a thin envelope reminiscent of the thin hydrogen envelope inferred from observations. Hence we can define a universal critical temperature $T_H$ below which the envelope becomes transparent leading to the optical excess. The rate of depletion of the envelope closely follows the cooling rate/curve. As such, the size of the envelope will drop quicker as the stars enter the faster cooling beyond the $10^{-10}$ years epoch. This one-to-one relationship could in principle account for the observed clustering in time and temperature of the 7 radio-quiet INSs as well as their associated optical excess. The critical temperature $T_H$ among others features inherent to our model and the observational consequences will be explored in more details in an upcoming paper. For now we are tempted to speculate that radio-quiet INSs are quark stars in the superconductive phase cooling through the slow release of photons from GLB decay or similar processes. For completeness, shown in Figure 4 are the time evolution of the temperature, $T_e^\infty$ (as seen by a distant observer) for $T_{GLB} = 1$ MeV, and for different star radius $R$. The cooling curves begin approximately 2 weeks after $t = 0$. The observed data are RX J185635-3754 (lower square) and RX J0720.4-3125 (upper square).

erg of photon energy can be provided by the GLB decay radiated away by the star over millions of years. The persistent blackbody emission offers a different picture from other models of cooling of quark stars where the photon spectrum is predicted to vary in time. Our fit to cooling data of observed INSs suggests that these are quark stars with extremely thin or no crust where GLB decay has taken effect. The fits favor gap energy $\Delta_{2SC} = 15$-$35$ MeV with corresponding densities $\rho_{2SC} = (2.5$-$3.0) \times 10^{14}$; this might be of relevance to Quantum-Chromodynamics. Let us state again that in principle our picture applies to quark stars where photon generation mechanisms are at play. If correct, our model combined with more observations of cooling of isolated compact stars, in particular hot radio-quiet ones, could be used to constrain other fundamental parameters of quark matter and its exotic phases.

6 CONCLUSION

In this work we investigated the effect of photons from GLB decay on the cooling history of quarks stars in the 2SC phase. While the early cooling history is dominated by neutrino emission, we find that further cooling is driven by photons, from the GLB decay, slowly diffusing out of the star. This cooling mechanism could be potentially important in situations or cases where the neutrino emission is heavily suppressed by pairing of quarks. Up to $10^{14} - 10^{17}$

Figure 4. The time evolution of the temperature, $T_e^\infty$ (as seen by a distant observer) for $T_{GLB} = 1$ MeV, and for different star radius $R$. The cooling curves begin approximately 2 weeks after $t = 0$. The observed data are RX J185635-3754 (lower square) and RX J0720.4-3125 (upper square).

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