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The missing compact star of SN1987A: a solid quark star?

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ABSTRACT

To investigate the missing compact star of Supernova 1987A (SN1987A), we analysed the cooling and heating processes of a possible compact star based on the upper limit of observational X-ray luminosity. From the cooling process, we found that a solid quark-cluster star (SQS), having a stiffer equation of state than that of a conventional liquid quark star, has a heat capacity much smaller than a neutron star. The SQS can cool down quickly, naturally explaining the non-detection of a point source in X-ray wavelengths. On the other hand, we considered the heating processes due to magnetospheric activity and possible accretion, and obtained some constraints on the parameters of a possible pulsar. Therefore, we concluded that an SQS can explain the observational limit in a confident parameter space. With a short period and a strong magnetic field (or with a long period and weak field), a pulsar would have a luminosity higher than the observational limit if the optical depth is not large enough to hide the compact star. As possible central compact objects, the parameters constrained for a pulsar can be tested for SN1987A with advanced facilities in the future.

Key words: elementary particles – stars: neutron – pulsars: general.

1 INTRODUCTION

Since the discovery of the first pulsar (Hewish et al. 1968), pulsars are thought to be rapidly rotating neutron stars (NSs). Until recently, the equation of state (EoS) of NSs remained unclear. Witten (1984) postulated that the true ground state of hadrons might be strange matter, containing roughly equal numbers of up, down and strange quarks. Quark stars (QSs) or strange stars (SSs) were then realized to be the ground state of NSs (Alcock, Farhi & Olinto 1986; Haensel, Zdunik & Schaeffer 1986). NSs may convert to QSs.

Are pulsars NSs or QSs? Essentially, the problem arises from non-perturbative quantum chromodynamics (QCD), which describes the strong interaction processes in low energy scales and is very hard to solve analytically in mathematics. Fortunately, astronomical observations can distinguish between NSs and QSs, as well as help to understand the non-perturbative QCD issue.

There are numerous methods that can constrain the EoSs of pulsars and check the differences of NSs and QSs. For example, QSs are self-bound, whereas NSs are gravity bound, yielding different mass–radius relations. Being able to measure the mass and radius of a pulsar would thereby classify it as either an NS or a QS. This has been unsuccessful until now, mainly due to uncertainties of the radii. Nevertheless, Li et al. (1999) suggested that SAX J1808.4-3658 may be a QS based on this relation and available data. Another constraint to consider is the minimum mass of a pulsar or a sub-millisecond pulsar. Since QSs are self-bound, their masses can be much smaller than the minimum mass of an NS, given that the mass of a QS could be smaller than $0.5\,M_\odot$ and can spin with a period shorter than 1 ms, whereas an NS cannot (Du et al. 2009). Therefore, if either the mass of a pulsar is smaller than $0.5\,M_\odot$ or has a period shorter than 1 ms, it could not be classified as an NS.

Different EoSs of pulsars yield different maximum masses. The recently verified mass of PSR J1614-2230 of $2\,M_\odot$ (Demorest et al. 2010) rules out almost all currently proposed hyperon or boson condensate EoSs (Lattimer & Prakash 2007) along with traditional soft EoSs of QSs (Chan et al. 2009). Lai & Xu (2009) postulated that the solid quark-cluster stars (SQSs, a special kind of QSs) could have a maximum mass larger than $2\ M_\odot$ due to its very stiff EoS.

The bolometric radiation of a young pulsar can distinguish between NSs and QSs, due to different thermal capacity and surface radiation. SQSs have very small thermal capacity since its temperature is much lower than the Debye temperature (Yu & Xu 2011). They can cool down quickly and have a very lower bolometric luminosity compared to an NS. This paper examines the missing compact object in Supernova 1987A (SN1987A; McCray 2007) and explores its luminosity constraint.

Without question, SN1987A provides an unprecedented opportunity in astronomy and astrophysical studies. However, the nature of the compact star produced during this explosion remains a mystery. On 1987 February 23, both the Kamiokande II detector and the Irvine–Michigan–Brookhaven detector observed a neutrino burst

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(Bionta et al. 1987; Hirata et al. 1987) within the Large Magellanic Cloud, just before the optical shine. The energy spectrum and flux density of the neutrino burst are consistent with the current theory of a core-collapse supernova releasing energy of $\sim 3 \times 10^{53}$ ergs, therein expecting a forming NS. Astronomers were excited by the possibility of watching an NS at its beginning. From that moment onwards, the powerful ground- and space-based instruments observed it from radio to gamma-ray wavelengths. Unfortunately, no pulses have been detected nor has a point source been found (Manchester 2007; McCray 2007).

The Parkes 64-m radio telescope was used to search for pulses from SN1987A within the first few years at frequencies between 400 and 5000 MHz, with a lower limit of $\sim$0.2 mJy at 1.5 GHz (Manchester 1988). Strong efforts were made with the Parkes telescope in 2006 in several bands; however, no pulsar candidates with a signal-to-noise ratio greater than 9.0 were detected (Manchester 2007). Some optical observations hinted at the detection of a pulsar in SN1987A (Kristian et al. 1989; Murdin 1990; Middleditch 2000); however, most of them have yet to be confirmed. Percival et al. (1995) performed an optical study using the *Hubble Space Telescope* (*HST*). Given a period range of 0.2 ms to 10 s with an upper limit for the pulsed emission equivalent to a V-band magnitude of $\sim$24, no significant pulsations were detected. A similar study was carried out by Manchester & Peterson (1996) using the 3.9-m Anglo-Australian Telescope with similar conditions, also yielding null results. Shtykovskiy et al. (2005) obtained a luminosity upper limit in the 2–10 keV band of 5×10^{34} erg s^{-1} using the *XMM–Newton*. Park et al. (2002, 2004) obtained upper limits of 5.5×10^{33} and 1.5×10^{34} erg s^{-1} in the same X-ray band using the *Chandra*.

To explain the non-detection of the expected NS, several possibilities were put forth. First, some ejected material from the supernova may fall back on to the NS surface shortly after the initial explosion. We have not been able to observe the NS since it may have converted into a black hole (BH) due to the in-falling material. But this possibility is unlikely. The discovery of a 2 $M_\odot$ pulsar (Demorest et al. 2010) suggests that the maximum mass of a pulsar could be much larger than 1.4 $M_\odot$; therefore, a normal NS has to accrete a large amount of material in order to convert into a BH. Secondly, the NS could be located within a cold dust cloud (McCray 2007) at the centre of SN1987A and may be opaque at various wavelengths. However, if the NS is not surrounded by dust or the dust is optically thin in X-ray bands, it would be very intriguing because the upper limit of around 1 keV is lower than the expected luminosity of a cooling NS without heating (McCray 2007; Park et al. 2007). Chan et al. (2009) postulated that the compact central star of SN1987A might not be an NS but a QS with a softer EoS, which could yield an X-ray luminosity less than 10^{34} erg s^{-1} at an age of 20 yr. We would like to note that the QS having this EoS is almost ruled out since the newly discovered 2 $M_\odot$ NS (Demorest et al. 2010), since its maximum mass is smaller than 2 $M_\odot$ due to its soft EoS.

A model for a QS with a stiff EoS, e.g. the SQS (Lai & Xu 2011), still remains a theoretical possibility. Xu (2003) first postulated the SQS, later improved by Zhou et al. (2004), Lai & Xu (2009) and Lai & Xu (2011). The interaction energy of quarks in a compact star could be higher than the Fermi energy when the density is lower than a few tens of nuclear densities (Xu 2011); therefore, quarks may be clustered and the star could be a solid QS, i.e. the SQS. The SQS model naturally explains most of the observational features of pulsars (Xu 2011). The surface of an SQS is self-bound, providing a larger bound energy than a gravity-bound NS, thereby more productive in the generation of radio emission (Xu, Qiao & Zhang 1999; Qiao et al. 2004). The X-ray emission and pulsations in its magnetosphere are similar to those of an NS. The star quake of an SQS induces glitches and energetic bursts which may be seen as soft gamma-ray repeaters (Xu, Tao & Yang 2006). The SQS could have a larger maximum mass than that of other model of QSs. Lai & Xu (2009) state a possible maximum mass $>2\,M_\odot$, surviving the test from the 2 $M_\odot$ pulsar (Demorest et al. 2010). The SQS has a smaller radius than any NS, given a small mass. The new discovery of the radius and mass of the rapid burster (MXB 1730-335; Sala et al. 2012) could naturally fit within the SQS model. Furthermore, the SQS has a very low heat capacity (Yu & Xu 2011), allowing it to cool down quickly. This may explain the non-detection of a point source in SN1987A.

In this work, we first analysed the cooling process of an SQS in comparison with an NS and a traditional liquid QS. Then, we studied the constraints on the parameters via the heating processes of pulsars. Our conclusions and discussions are presented in Section 4.

2 COOLING OF THE POSSIBLE COMPACT OBJECT

A stellar BH has no classical radiation with a negligible Hawking radiation in astronomy; therefore, its cooling luminosity is nearly zero. For NSs and QSs, the cooling processes are classified through their heat capacities and surface radiation.

The heat capacities of NSs, conventional QSs and SQSs (Maxwell 1979; Ng, Cheng & Chu 2003; Yu & Xu 2011) are defined as

$$C_{\rm NS} = C^{\rm n}_{\rm NS} + C^{\rm e}_{\rm NS}, \tag{1}$$

$$C_{\rm SS} = C^{\rm q}_{\rm SS} + C^{{\rm g}-\gamma}_{\rm SS} + C^{\rm e}_{\rm SS}, \tag{2}$$

$$C_{\rm SQS} = C^{\rm l}_{\rm SQS} + C^{\rm e}_{\rm SQS}, \tag{3}$$

respectively, where the superscripts n, e, q, g–γ and l denote the contributions from neutrons, electrons, quarks, quark–gluon plasma and lattice structure, respectively. In equations (1) and (2), $C^{\rm n}_{\rm NS}$ and $C^{\rm q}_{\rm SS}$ are larger than $C^{\rm e}_{\rm NS}$ and $C^{\rm e}_{\rm SS}$ when the temperature is higher than the critical temperature, $T_{\rm c}$ ($\sim 10^9$ K). When $T < T_{\rm c}$, the superfluid state dominates; therefore, $C^{\rm n}_{\rm NS}$ and $C^{\rm q}_{\rm SS}$ will decay exponentially and vanish quickly. In equations (2) and (3), both $C^{{\rm g}-\gamma}_{\rm SS}$ and $C^{\rm l}_{\rm SQS}$ are proportional to T^3, whereas $C^{\rm e}_{\rm SS}$ and $C^{\rm e}_{\rm SQS}$ are proportional to T. Thus, the heat capacity of compact stars is dominated by electrons when the temperature is not too high, with $T_{\rm c} \sim 10^9$ K for NSs and QSs, and $\sim 10^{10}$ K for SQSs (Yu & Xu 2011). Otherwise, the temperature will cool down quickly below 10^9 K within dozens of seconds. Therefore, the heat capacity of electrons overwhelms the cooling process within an observational time. The heat capacity of electrons in NSs, conventional QSs and SQSs (Maxwell 1979; Ng et al. 2003; Yu & Xu 2011) is defined as

$$C^{\rm e}_{\rm NS} = 1.9 \times 10^{37} M_1 \rho_{14}^{1/3} T_9 \ {\rm erg\ K^{-1}}, \tag{4}$$

$$c^{\rm e}_{\rm SS} = 1.7 \times 10^{20} (Y\rho/\rho_0)^{2/3} T_9 \ {\rm erg\ (cm^3\ K)^{-1}}, \tag{5}$$

$$C^{\rm e}_{\rm SQS} \simeq N_{\rm e} \frac{k_{\rm B} T_{\rm s}}{E_{\rm F}} k_{\rm B}, \tag{6}$$

respectively, where $M_1 = M/{\rm M}_\odot$, $\rho_{14} = \rho/10^{14}$ g cm^{-3}, $T_9 = T/10^9$ K, Y is the electron fraction, ρ_0 the nuclear matter density, $N_{\rm e}$ the electron number in a star, $k_{\rm B}$ Boltzmann's constant, $T_{\rm s}$ the value in the star's local reference frame and $E_{\rm F}$ the Fermi energy of the degenerate electron gas. In the extremely relativistic case, $E_{\rm F} = (\frac{3 n_{\rm e} h^3}{8\pi})^{1/3} c$, where $n_{\rm e}$ is the number density of electrons,

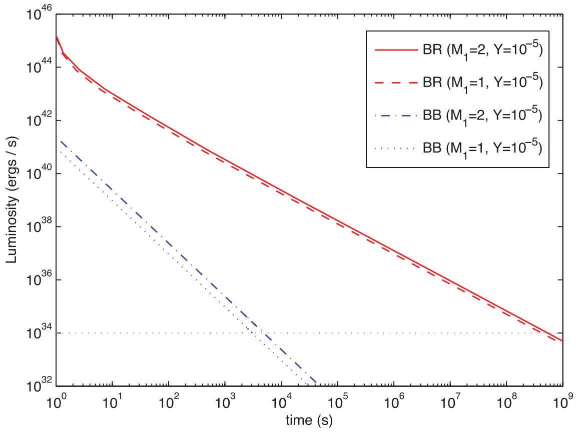

Figure 1. The cooling curves of SQSs with bremsstrahlung (BR; Caron & Zhitnitsky 2009) and blackbody radiation (BB). The neutrino radiation and colour superconductivity-related photon emission are not considered. The observational upper limit is indicated as a horizontal dotted line. It shows that the cooling luminosity of an SQS could be smaller than 10^{34} ergs s^{-1} about 20 yr after its birth even when it cools down by bremsstrahlung emission. Here we take the stellar mass $M = M_1\,\mathrm{M}_\odot$ and the number ratio of electron to baryon as Y.

h the Planck constant and c the speed of light. From equation (6), we found

$$C^{\mathrm{e}}_{\mathrm{SQS}} \simeq 3.5 \times 10^{37} (Y M_1)^{2/3} R_6 T_9 \,\mathrm{erg\ K^{-1}}, \quad (7)$$

where R_6 is the stellar radius in units of 10^6 cm. The electron number in a QS is much smaller than that in an NS, $Y \sim 10^{-5}$. Thus, the heat energy conserved in a QS is far less than in an NS.

Surface radiation plays an important role in the cooling process. On the surface of an NS, radiation can be simply treated as an approximate blackbody radiation because of an atomic atmosphere. On the surface of a conventional QS or an SQS, however, there is no atomic atmosphere; therefore, its radiation mainly depends on the interaction between the electric layer and photons. Chan et al. (2009) postulated that the surface radiation of a QS is caused through bremsstrahlung radiation and predicted a luminosity less than 10^{34} erg s^{-1} with an age older than 20 yr. In their paper, they used the bremsstrahlung calculations of Jaikumar et al. (2004). We note that Caron & Zhitnitsky (2009) obtained a much lower flux from the QS bremsstrahlung emission. In this work, we adopted the formula from Caron & Zhitnitsky (2009) to calculate the cooling processes of an SQS, thereby making our results more reliable.

Fig. 1 shows the bremsstrahlung cooling curves of an SQS (Lai, Gao & Xu 2011) along with those of the blackbody radiation. We ignored neutrino radiation and colour superconductivity-related photon emission mechanisms. We found that the cooling luminosity of an SQS could be smaller than 10^{34} ergs s^{-1} roughly 20 yr after its birth, as it cools down through bremsstrahlung emission. The other possible emission mechanisms would make an SQS cool down faster. Therefore, we can conclude that the presence of a cooling SQS in SN1987A should be currently undetectable, which coincides with the observations.

3 CONSTRAINTS ON THE PARAMETERS VIA HEATING PROCESSES

The bolometric luminosity of a compact star arises not only from the contribution of a cooling process but also from heating processes due to the activity of magnetosphere and the accretion of the interstellar medium (ISM) and accretion discs. The heating luminosity is most likely lower than the upper limit of current observations. The heating mechanisms are independent of the EoS of a pulsar; therefore, constraints on the physical parameters of a possible pulsar can be put forth, whether or not it is an NS or an SQS.

Typically, the activity of the magnetosphere can produce both thermal and non-thermal X-ray emissions. When particles accelerate within the magnetosphere, they emit non-thermal X-rays with a power-law spectrum. On the other hand, when particles fall in and bombard the surface of a pulsar, they will heat the surface, thereby producing thermal X-rays. Becker & Trümper (1979) found that the non-thermal X-ray luminosity L_{x} and spin-down energy loss rate $\dot{E}$ roughly correlate as $L_{\mathrm{x}} = 10^{-3}\dot{E}$. Yu & Xu (2011) also found that the thermal X-ray luminosity has a similar relation with $\dot{E}$, as $L^{\infty}_{\mathrm{bol}} \sim 10^{-3}\dot{E}$. Since observations provide an upper limit for thermal X-ray luminosity $L^{\infty}_{\mathrm{bol}} \sim 10^{34}$ erg s^{-1} (Park et al. 2002, 2004), we can obtain an upper limit of the spin-energy loss rate $\dot{E}$. Furthermore, we can constrain the parameters of the spin and the magnetic field of the possible pulsar, since $\dot{E}$ depends on the spin and magnetic field as

$$\dot{E} = -\frac{2}{3c^3}\,\mu_\perp^2 \Omega^4, \quad (8)$$

where $\mu_\perp$ and Ω are the vertical fraction of the magnetic moment μ and the spin angular frequency of the pulsar, respectively. We define a parameter a as the factor of thermal X-ray luminosity in terms of spin-down energy loss rate, i.e.

$$L^{\infty}_{\mathrm{bol}} = a\dot{E}, \quad (9)$$

yielding

$$\mu \simeq 3.22 \times 10^{14} a^{-1/2} L^{\infty\ 1/2}_{\mathrm{bol}} P^2, \quad (10)$$

where $P = 2\pi/\Omega$ is the spin period of a pulsar.

We note that most pulsars have an X-ray luminosity of 10^{-4}–$10^{-2}\dot{E}$ in both thermal and non-thermal cases (Becker & Trümper 1979; Yu & Xu 2011). We confined $a = 10^{-4}$, 10^{-3} and 10^{-2} to obtain the upper-left three lines in two panels of Fig. 2. In both panels, the regions left of the dash–dotted lines should be

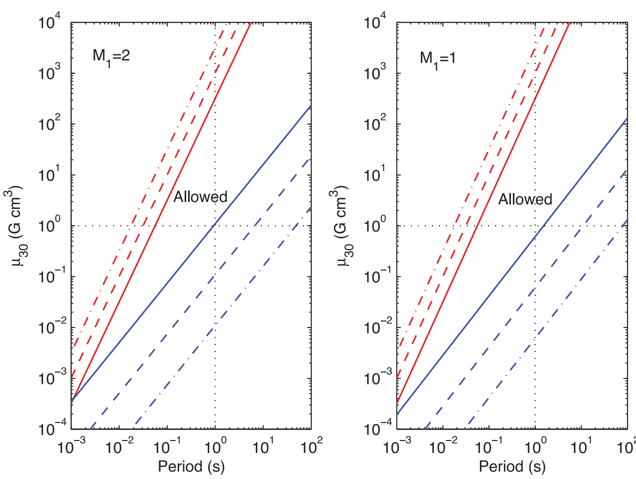

Figure 2. Constraints on parameters of the possible compact object in SN1987A via magnetosphere action heating (upper-left three lines) and fall-back disc accretion heating (lower-right three lines). Left-hand panel: $M_1 = 2$ and $b = 0.9$, $a = 10^{-4}$ for red dash–dotted line, $a = 10^{-3}$ for red dashed line, $a = 10^{-2}$ for red solid line, $\dot{M} = 10^{18}$ erg s^{-1} for blue solid line, $\dot{M} = 10^{16}$ erg s^{-1} for blue dashed line and $\dot{M} = 10^{14}$ erg s^{-1} for blue dash–dotted line. Right-hand panel: same as the left but $M_1 = 1$.

excluded since the X-ray factor can be as small as 10^{-4}; therefore, its luminosity should be larger than 10^{34} erg s^{-1}. The regions below the solid lines should be comparable with the observational upper limit, since the X-ray luminosity is less than 10^{34} erg s^{-1}, even with $a = 10^{-2}$.

The accretion heating mechanism has also been used to restrict pulsar parameters. The accretion from the ISM is strongly dependent on the proper motion of a pulsar, typically with a very negligible luminosity. Here, we considered the possible accretion due to the fall-back disc.

The evolution of the fall-back disc requires three radii: the light speed radius $r_{\rm L}$, the co-rotation radius $r_{\rm co}$ and the magnetosphere radius $r_{\rm m}$, defined as

$$r_{\rm L} = cP/2\pi, \tag{11}$$

$$r_{\rm co} = (GM/4\pi^2)^{1/3} P^{2/3}, \tag{12}$$

$$r_{\rm m} = \mu^{4/7} (2GM)^{-1/7} \dot{M}^{-2/7}, \tag{13}$$

respectively, where G, M and $\dot{M}$ are the gravitational constant, the pulsar mass and accretion rate, respectively. The fall-back disc regime of a pulsar often undergoes three phases: (1) pulse phase, (2) propeller phase and (3) accretion phase. The pulse phase occurs in the early stage of a pulsar, when it has a fast spin and strong radiation pushing the ISM out beyond the light speed radius $r_{\rm L}$, thereby causing the compact star to act like a pulsar. When the radiation decreases, some of the ISM may fall back within the light speed radius and interact with the magnetosphere. When $r_{\rm co} < r_{\rm m} < r_{\rm L}$ or even when $r_{\rm m}$ is just a little smaller than $r_{\rm co}$, the magnetic freezing effect would force the flow of the medium to corotate with the pulsar, thereby transferring the spin energy of the pulsar to the ISM through interaction. This is the so-called propeller phase. During this phase only a small amount of the ISM can diffuse and fall back on the surface, thereby inducing the low-luminosity X-ray emission. If the accreted material crosses the corotation radius and accesses the so-called break radius $r_{\rm br}$, which is a little smaller than $r_{\rm co}$ (i.e. $r_{\rm m} < r_{\rm br} < r_{\rm co}$), then a massive accretion event would occur. This is the accretion phase, causing the pulsar to produce a very large X-ray luminosity.

The *HST* found dust clouds interior to the debris in SN1987A (McCray 2007), indicative of the formation of a fall-back disc around the central compact star. If the fall-back disc exists, then we would expect the pulsar to be in a phase prior to the accretion phase, which would result in an X-ray luminosity larger than 10^{34} erg s^{-1}. Thus, the disc should have $r_{\rm m} > r_{\rm br}$. We presumed that $r_{\rm br}$ is proportional to $r_{\rm co}$, i.e. $r_{\rm br} = br_{\rm co}$, where b is a constant and $0 < b < 1$. Therefore, in order to fit the model with observations, we need

$$r_{\rm m} > br_{\rm co}. \tag{14}$$

Applying $r_{\rm m}$ and $r_{\rm co}$ to the above equation, we obtain the relation of the pulsar parameters,

$$\mu_{30} > 0.074 b^{7/4} {M_1}^{5/6} \dot{M}_{16}^{1/2} P^{7/6}, \tag{15}$$

where $\mu_{30} = \mu/10^{30}$ and $\dot{M}_{16} = \dot{M}/10^{16}$.

The lower-right three lines in both panels of Fig. 2 show that the magnetic moment depends on the spin period along with other given parameters. We set $b = 0.9$ in both cases, $M_1 = 2$ (left) and $M_1 = 1$ (right). We set the accretion rate from $\dot{M} = 10^{18}$ to 10^{14} g s^{-1}. We note that when $\dot{M} < 10^{14}$ g s^{-1}, the heating luminosity cannot exceed 10^{34} erg s^{-1} even during the accretion phase. For a disc surrounding a pulsar, it is almost impossible for the accretion rate to exceed 10^{18} erg s^{-1}.

Therefore, the two heating mechanisms provide two sets of limits to the parameters for a possible pulsar, as shown in Fig. 2. Combining both heating mechanisms, the region between the two solid lines is compatible with observations, while the upper-left and lower-right regions are the forbidden zones. Comparing the left-hand and right-hand panels, we note that pulsars with a smaller mass have a wider region of parameters, as opposed to that for massive pulsars. Since the heating mechanisms are EoS independent, our results can be applied to both NSs and QSs.

4 CONCLUSIONS AND DISCUSSIONS

We analysed the cooling processes of compact stars and found that SQSs could have a thermal luminosity lower than the observational upper limit for SN1987A. We examined the possible heating processes of a young pulsar and obtained constraints on the pulsar's parameters. It should be reasonable to conclude the following.

(i) An SQS with normal parameters is compatible with the non-detection in SN1987A, since both of its cooling and heating luminosities should be lower than the observational upper limit. A low-mass QS has a wider parameter space than a more massive one.

(ii) If the compact star is surrounded by dust, the parameter constraints become relaxed. The parameter space of an SQS is wider than that of a normal NS.

(iii) However, a BH candidate cannot be excluded through cooling and heating analysis, although it is very difficult to form via accretion.

The predicted parameter space discussed here could be tested by future observations. The impact of the supernova blast wave with its circumstellar matter is producing a visible ring from mm to X-ray wavelengths for SN1987A (Bouchet et al. 2006; Gaensler et al. 2007; McCray 2007; France et al. 2010) and it is still getting brighter. This ring would make it almost impossible to detect or rule out a cooling compact star in these bands. However, a heating pulsar may be detected in the future due to the very slow decay of the heating luminosity from magnetospheric activity. When the fall-back disc evolves into the accretion phase, the X-ray luminosity could be much larger than that in prior phases, finally rendering the central star to be detectable. It remains unclear whether the low-frequency radio and high-energy gamma-ray bands are affected by the ring, which preserves the possibility of discovering the compact star and test the parameters through future advanced facilities, e.g. the Square Kilometre Array telescope.

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