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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, we analysed both the cooling and the heating processes of a possible compact star based on the observational X-ray luminosity upper limit. From the cooling process we found that a solid quark cluster star (Lai & Xu 2011), with harder equation of state than liquid quark star, has heat capacity much smaller than neutron star and would cool quickly below the observational X-ray luminosity upper limit, which can naturally explain the non-detection of a point source (neutron star or quark star) in X-ray band. On the other hand, we considered the heating process from magnetospheric activity and possible accretion and obtained some constraints to the parameters of a possible pulsar. We conclude that a solid quark cluster star can accord with the observational limit in a large and normal parameter space, while a pulsar with short period and strong magnetic field (or with long period and weak field) would has luminosity higher than the limit if the optical depth is not large enough to hide the compact star. We expect that the constraints would be tested if the central compact object in 1987A could be discovered by advanced facilities (e.g., in radio bands) in the future.

Key words: pulsar: general – elementary particles – supernovae – star: neutron

1 INTRODUCTION

Pulsars are traditionally regarded as neutron stars (NSs) since the discovery of the first pulsar (Hewish et al. 1968). Nevertheless, the equation of state (EoS) of neutron star is not clear till now. Witten (1984) pointed out that the true ground state of hadrons may be strange matter, which contains roughly equal numbers of up, down and strange quarks. It is then people realized that quark star or strange star (SS) might be the ground state of NSs (Alcock et al. 1986; Haensel et al. 1986), thus NSs may convert to SSs.

Are pulsars NSs or SSs? Essentially, this is a problem of non-perturbative quantum chromodynamics (QCD), which describes the strong interaction processes in low energy scale, and is very hard to solve in mathematics. Fortunately, the astronomical observations could be capable of discriminating NSs and SSs thus would contribute to understand the non-perturbative QCD issue.

There are as much methods to test the EoSs of pulsars as the differences between NSs and SSs. For example, SSs are self-constraint while NSs are gravity constraint thus they have different mass-radius relations. If we can detect a pulsar's mass and its radius, we can discriminate whether it is a NS or a SS. This method doesn't succeed up to now mainly because there are too much uncertainties in confirming the radius of any compact object. Another testing is the minimum mass of pulsar and the sub-millisecond pulsar. Since the SSs are self-constraint, their mass can be much smaller than the minimum mass of NS, which is about $0.1M_{\odot}$, and can spin with period shorter than 1 millisecond while the NS can't (Du et al. 2009). Thus if a pulsar mass is smaller than $0.1M_{\odot}$ or its period is shorter than 1 millisecond, it could not be a NS. The maximum mass of pulsar can also be useful. Different EoS of pulsar gives different maximum mass, thus the confirmed largest mass of pulsar can rule out those EoSs which don't accord with it. The new confirmed massive pulsar PSR J1614-2230, $2M_{\odot}$ (Demorest et al. 2010) rules out almost all currently proposed hyperon or boson condensate EoSs (Lattimer & Prakash 2007) and traditional soft EoS of SS (Chan et al. 2009), but still can't finally verify whether it is a NS or a SS. Lai & Xu (2011) suggested that solid quark cluster stars (SQS), a special kind of SS, could have very stiff EoS thus the maximum mass can even reach to 3 $M_{\odot}$.

Besides the above methods, the bolometric radiation of a young pulsar could also make a distinction between NSs and SSs, because they are different in thermal capacity and surface radiation, which we will study in detail in this work. We note that a SQS has very small thermal capacity, because its temperature is much lower than the Debye temperature (Yu & Xu 2011), thus can cool very fast and has very lower bolometric luminosity than NSs. The missing compact object in SN1987A (McCray 2007) will be studied from this point of view in this paper.

There is no doubt that SN1987A provides an unprecedented opportunity in astronomy and astrophysics studies. Yet the implied compact star in this exploding is still a mystery. On 23 February 1987, the Kamiokande II detector and the Irvine-Michigan-

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Brookhaven detector both observed a neutrino burst (Hirata et al. 1987; Bionta et al. 1987) from the Large Magellanic Cloud, just before the optical sighting of SN1987A . The energy spectral and the flux density of the neutrino burst correspond with the current theory of core-collapse supernova burst with $\sim 3\times 10^{53}$ ergs energy released, which is expected to construct a NS therein. People are excited by the possibility of studying a NS at its very beginning. From then on, the powerful detectors on the ground and in the space searched it from radio to gamma ray bands, one after another. Unfortunately, they didn't find any pulses or a point source there (McCray 2007; Manchester 2007).

Despite the low probability of a detection in radio bands in the first few years, Parkes 64-m radio telescope searched SN1987A at frequencies between 400 and 5000 MHz and gave an upper limit $\sim$0.2 mJy at 1.5 GHz (Manchester 1988). The followed observations obtained similar parameters and upper limits. The best search was carried out at Parkes in 2006 in several bands, but no significant candidates with a S/N ratio greater than 9.0 were observed (Manchester 2007). Some optical observations announced the detection of a pulsar in SN1987A (Kristian et al. 1989; Murdin 1990; Middleditch 2000), but all were proved to be wrong or have not been confirmed at last. Percival et al. (1995) reported an optical search using Hubble Space Telescope, which observed no significant pulsations in the period range 0.2 ms to 10 s with an upper limit for the pulsed emission equivalent to a V magnitude of $\sim$24. A similar search was reported by Manchester & Peterson (1996) using 3.9-m Anglo-Australian Telescope with similar parameters and results. Shtykovskiy et al. (2005) obtained a luminosity limit in the 2-10 keV band of 5×10^{34} erg s^{-1} using XMM-Newton. Park et al. (2002, 2004) obtained upper limits of 5.5×10^{33} erg s^{-1} and 1.5×10^{34} erg s^{-1} in the same band using Chandra. Note that the interaction between the shock and the interstellar medium is making the supernova remnant brightening (McCray 2007), the limit is increasing.

To explain the non-detection of the predicted NS, several schemes are proposed. First, some of the ejected material may fell back to the NS surface shortly after the supernova burst and changed it to a black hole (BH), thus we can't find the NS since it has converted to a BH. Another possible situation is that the NS may be located in the cold dust cloud (McCray 2007) at the center of SN1987A, which is opaque to photons in some band. But if the NS is not inside the dust or the dust is optical thin, it would be very interesting because the observed upper limit at around 1 keV is already lower than the expected luminosity of a cooling NS with no heating (Park et al. 2007; McCray 2007). Chan et al. (2009) suggested that the compact star at the center of SN1987A may be not a NS but a SS with softer EoS than that of neutron star matter, which could have X-ray luminosity less than 10^{34} erg s^{-1} at its 20 year age. Note that this SS is almost ruled out by the new found 2 $M_\odot$ NS (Demorest et al. 2010), because its maximum mass is smaller than that detected due to softer EoS. But the quark stars with stiff EoS are still possible, e.g. the SQS (Lai & Xu 2011).

In this work we will first analyze the cooling process of SQS contrast with NS and traditional liquid SS, and then further study the constraints on the parameters via heating processes. The last section is our discussions and conclusions.

2 COOLING OF THE POSSIBLE CANDIDATES

For a stellar mass BH, it has no classical radiation, even its Hawking radiation is absolutely negligible in astronomy, thus its cooling luminosity is zero. For NSs and SSs, the cooling processes are determined by their heat capacities and surface radiations.

The heat capacities of NS, conventional SS and SQS are as follows (Maxwell 1979; Ng et al. 2003; Yu & Xu 2011),

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

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

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

where the superscripts n, e, q, g-γ, and l, denote the contributions of neutrons, electrons, quarks, quark-gluon plasma and lattice structure, respectively. In eqs. (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 temperature is higher than critical temperature T_c ($\sim 10^9$ K). When $T < T_c$ the superfluid state appears, $C^{\rm n}_{\rm NS}$ and $C^{\rm q}_{\rm SS}$ will exponential decay and vanish quickly. In eqs. (2) and (3), $C^{\rm g-\gamma}_{\rm SS}$ and $C^{\rm l}_{\rm SQS}$ are both in proportion to T^3, while $C^{\rm e}_{\rm SS}$ and $C^{\rm e}_{\rm SQS}$ are in proportion to T. Thus the heat capacities of all of these compact stars would be dominated by the contribution of electrons when temperature is not too high, which is $\sim 10^9$K for NS and SS, and $\sim 10^{10}$K for SQS (Yu & Xu 2011). These compact stars' temperatures will quickly reduce below 10^9K within dozens of seconds. Therefore, the heat capacities of electrons dominate the cooling process in almost all the observational time. The heat capacities of electrons in NS, SS and SQS are summarized as following (Maxwell 1979; Ng et al. 2003; Yu & Xu 2011),

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

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

$$C^{\rm e}_{\rm SQS} \simeq N_e \frac{k_B T_s}{E_F}\, k_B, \tag{6}$$

where $M_1 = M/M_\odot$, $\rho_{14} = \rho/10^{14}$ g cm^{-3}, $T_9 = T/10^9$ K, Y is the electron fraction, ρ_0 is nuclear matter density, N_e is the electron number in a star, k_B is Boltzmann's constant, T_s is the value in the star's local reference frame, and E_F is the Fermi energy of the degenerate electron gas. In the extremely relativistic case, $E_F = (\frac{3 n_e h^3}{8\pi})^{1/3} c$, where n_e is the number density of electrons, h is Planck's constant, and c is the speed of light. From eq. (6) we have

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

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

Surface radiation is another important factor that determines the cooling process. On the NS surface, the radiation can be simply treated as approximate black body radiation because of the effect of atomic atmosphere. On SS or SQS surface there is no atomic atmosphere, therefore the radiation mainly depends on the interaction between electric layer and photons. Chan et al. (2009) suggested that the surface radiation of SS is bremsstrahlung, and predicted a luminosity smaller than 10^{34} erg s^{-1} when it is older than 20 years. The cooling curves of SQSs with different masses and electron fractions are shown in Figure 1, where we used the model of Lai et al. (2011), presumed black boldy radiation and ignored the neutrino radiation. It shows that the luminosity of cooling SQSs would be smaller than 10^{34} ergs s^{-1} only a few days after the birth. And because $C_{\rm SQS}$ is a little smaller than $C_{\rm SS}$, the luminosity of cooling SQS would lower than the upper limit even it emits by bremsstrahlung.

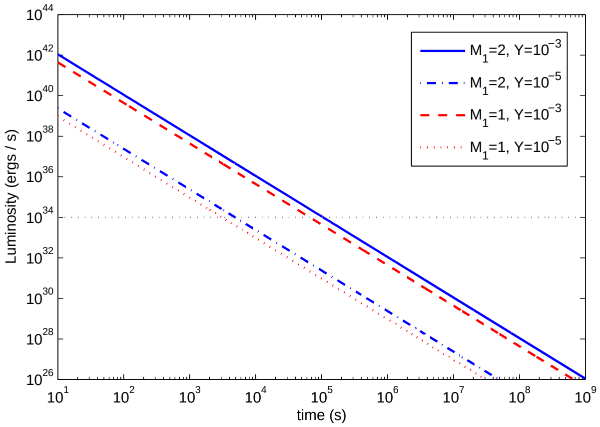

Figure 1. The cooling curves of SQSs with black body radiation. Neutrino radiation is not taken into account. The observational upper limit is marked with a horizontal dotted line. Here we have stellar mass $M = M_1 M_\odot$ and the number ratio of electron to baryon Y.

3 CONSTRAINTS ON THE PARAMETERS VIA HEATING PROCESSES

The bolometric luminosity of a compact star is not only the contribution of cooling process, but also of heating processes, which include the activity of magnetosphere and the accretion from interstellar medium and accretion disks. The heating luminosity should also be lower than the upper limit to accord with the observations.

Usually, the activity of magnetosphere can produce both thermal and non-thermal X-ray emissions. When particles are accelerated in the magnetosphere they can emit non-thermal X-rays with power law spectrum. When particles go in and bombard on the pulsar surface they will heat it and emit thermal X-rays. Becker & Trümper (1979) found that the non-thermal X-ray luminosity L_x and spin down energy loss rate $\dot{E}$ have a rough relation of $L_x = 10^{-3} \mid \dot{E} \mid$. Yu & Xu (2011) found the thermal X-ray luminosity also has the similar relation with energy loss rate, $L_{bol}^{\infty} \sim 10^{-3} \mid \dot{E} \mid$. Since the observations have given a upper limit of thermal X-ray luminosity $L_{bol}^{\infty} \sim 10^{34}$ erg s^{-1} (Park et al. 2002, 2004), we can get a upper limit of spin energy loss rate $\dot{E}$. And we can further make a restraint to the parameters of spin and magnetic field of the implied pulsar because $\dot{E}$ is the function of spin and magnetic field,

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

where $\mu_\perp$ and Ω are the vertical fraction of magnetic moment μ and the spin angular frequency of pulsar. We use a parameter a to present the section of thermal X-ray luminosity in spin down energy lost rate, i.e.

$$L_{bol}^{\infty} = a \mid \dot{E} \mid . \tag{9}$$

And then we get

$$\mu \simeq 3.22 \times 10^{14} a^{-1/2} L_{bol}^{\infty}{}^{1/2} P^2, \tag{10}$$

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

Note that most of the pulsars have X-ray luminosity in the region of $10^{-4} - 10^{-2}\dot{E}$ in both cases (Becker & Trümper 1979; Yu & Xu 2011), we used $a = 10^{-4}$, 10^{-3} and 10^{-2} for the upper left three lines in both panels of Figure 2. In the figure, the region to the left of the dash-dotted line should be ruled out because even the X-ray component is as small as 10^{-4}, it's luminosity should be larger than 10^{34} erg s^{-1}. The region below the solid line should be safe, because the X-ray luminosity is smaller than 10^{34} erg s^{-1} even the component is as large as 10^{-2}. The region between those two lines is somewhat uncertain.

The accretion heating can also give a restriction to the pulsar parameters. The accretion from interstellar medium is intensively dependent on the proper motion of pulsar, and usually has small luminosity. Thus we ignore it and only consider the possible accretion from fall back disk.

In fall back disk regime a pulsar often undergoes three phases: pulse phase, propeller phase and accretion phase. To understand the evolution of fall back disk we have three radius: the light speed radius r_L, the co-rotation radius r_{co} and the magnetosphere radius r_m, as,

$$r_L = cP/2\pi, \tag{11}$$

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

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

where G, M and $\dot{M}$ are the gravitational constant, the mass of pulsar and the accretion rate, respectively. The pulse phase exists in early stage of a pulsar, when the young pulsar has fast spin and strong radiations which push the interstellar medium out of the light speed radius r_L, thus the compact star acts as a pulsar. When the radiation becomes not so strong some of the medium may go into the light radius and interact with the magnetosphere. When $r_{co} < r_m < r_L$ or even r_m is a little smaller than r_{co}, the magnetic freezing effect would force the going in medium to co-rotate with the pulsar and the spin energy of pulsar will transfer to the medium via the interaction. This is so called propeller phase. In this phase there is little medium can diffuse and fall on the star surface and emit low luminosity X-ray. If the accretion material can across the co-rotation radius and access a so called break radius r_{br}, which is a little smaller than r_{co} (i.e. $r_m < r_{br} < r_{co}$), a massive accretion would occur. This is the accretion phase, which usually has very large X-ray luminosity.

The Hubble Space Telescope found a dust clouds interior debris in SN1987A (McCray 2007), which could be in favor of the formation of a fall back disk around the centra compact star. If the fall back disk do exist, we would expect the pulsar is not in accretion phase which usually results in X-ray luminosity larger than 10^{34} erg s^{-1}. Thus the disk should be expected to has $r_m > r_{br}$. We presume r_{br} is proportion to r_{co}, i.e. $r_{br} = br_{co}$, where b is a constant and $0 < b < 1$. Therefor to accord with the observations we need

$$r_m > br_{co}, \tag{14}$$

Submitting r_m and r_{co} to the above inequation, we get 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 Figure 2 show the magnetic moment depend on spin period with given parameters. We presumed $b = 0.9$ in both cases, $M_1 = 2$ for left and $M_1 = 1$ for right. And we used accretion rate from $\dot{M} = 10^{18}$ g s^{-1} to $\dot{M} = 10^{14}$ g s^{-1} in this figure. It should be noticed that when $\dot{M} < 10^{14}$ g s^{-1} the heating luminosity can't exceed 10^{34} erg s^{-1} even in the accretion phase, and for a disk around a pulsar the accretion rate is almost impossible to exceed 10^{18} erg s^{-1}.

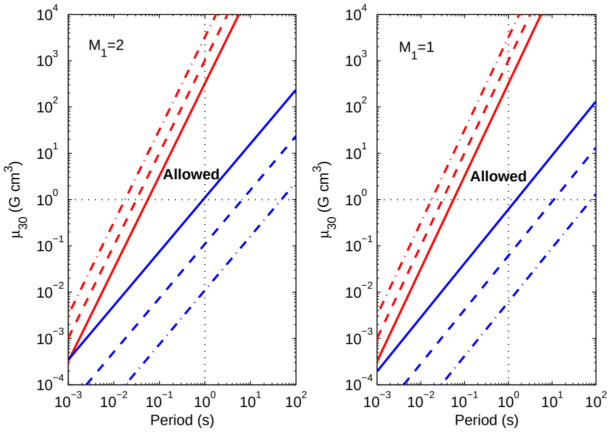

Figure 2. Constraints on the parameters of the possible compact object in SN1987A via magnetosphere action heating (upper left three lines) and fall back disk accretion heating (lower right three lines). Left panel: $M_1 = 2$ and $b = 0.9$ for all. $a = 10^{-4}$ for red dash-dotted line, $a = 10^{-3}$ 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-doted line. Right panel: $M_1 = 1$, other parameters are all the same.

In this section, two kinds of heating mechanisms provide two kinds of limit to the parameters of a possible pulsar, as shown in Figure 2. From the combination of both heating mechanisms, the region between two solid lines is safe, while the upper left and lower right regions are dangerous in some conditions. From the comparison of left panel and right panel we can see that the smaller pulsar has wider safe region than the bigger one.

4 CONCLUSIONS AND DISCUSSIONS

In this work we first analysed the cooling processes of compact stars and found that the SQSs could have thermal luminosity lower than the observational upper limit of SN1987A. And then we studied the possible heating processes of a young pulsar and obtained some constraints on the pulsar parameters. Combining with other contributions about SN1987A it should be reasonable to come to the following conclusions.

(i) A solid quark cluster star with normal parameters is in accord with the non-detection in SN1987A, because both its cooling and heating luminosities are lower than the observational upper limit. A low mass quark star has wider possible parameter space than a high mass one.

(ii) If the compact star is shielded by opaque dust, the constraints to the candidates and parameters should be relaxed, i.e. the parameter space of a SQS can be wider or even it can be a normal NS.

(iii) However, a black hole candidate can't be ruled out by cooling and heating analysis.

Also the predicted parameters in this paper could be tested by the future observations. The impact of the supernova blast wave with its circumstellar matter is producing a ring which is visible from mm-band to X-ray band (Bouchet et al. 2006; Gaensler et al. 2007; McCray 2007; France et al. 2010) and is still brightening. This ring would make it almost impossible to detect or rule out a cooling compact star in these bands. But a heating pulsar may be detected in the future because the heating luminosity from magnetospheric activity decays very slowly, and when the fall back disk evolves into accretion phase the X-ray luminosity could be much larger than in other phases thus could be detectable. Besides, there is no observational evidence showing whether the low frequency radio and γ-ray bands are effected by the ring, which preserves the possibility of discovering the compact star and test the parameters by the future advanced facilities, e.g. the Square Kilometer Array (SKA) telescope.

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