Signatures of QCD phase transition in a newborn compact star

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ABSTRACT

We study the scenario that a newborn strange quark star cools to the quantum chromodynamics (QCD) phase transition temperature and converts to a neutron star, and we calculate the evolution of temperature and luminosity of the compact star. We argue that the conversion energy released can be of the order of 10^{53} erg. We also propose that a second neutrino burst will be emitted at the completion of this phase transition.

Key words: dense matter – neutrinos – stars: neutron.

1 INTRODUCTION

The Bodmer–Witten proposal that symmetric deconfined u,d,s-quark matter may be the absolute ground state of matter and forms the so-called strange stars (Bodmer 1971; Witten 1984) has aroused much interest, and the properties of strange stars have been widely studied (Farhi & Jaffe 1984; Alcock, Farhi & Olinto 1986; Haensel, Zdunik & Schaeffer 1986; Cheng, Dai & Lu 1998; Glendenning 1996). An important question is whether the observed compact stars are neutron stars or strange stars. One possibility to distinguish the two is to study their cooling curves, which are significantly different (Usov 1998, 2001; Weber 1999; Ng et al. 2003; Page & Usov 2002).

In this paper, we study the effects of the quantum chromodynamics (QCD) phase transition on the cooling of a compact star and possible signatures of the quark phase. Regardless of the validity of the Bodmer–Witten proposal, the formation of quark–gluon plasma should be favoured in high temperature and density (Shuryak 1988); we therefore suggest that a strange star may be formed just after a supernova explosion, in which both conditions are satisfied (Benvenuto & Lugones 1999). Because the initial temperature is so high (Petschek 1990) $T_i \sim 40$ MeV, the initial compact star is likely to be a bare strange star (Usov 2001). When it cools down to the phase transition temperature T_p, the quark matter becomes energetically unstable compared with nuclear matter, and the strange star will convert to a neutron star. The conversion energy released during this QCD phase transition can be of the order 10^{53} erg. The temperature drops drastically at the completion of the phase transition, which is accompanied by the emission of a second neutrino burst owing to the higher neutrino emissivity of neutron matter.

In Section 2, we will first present the equation of state (EOS) that we use in the calculation for the quark phase. This is then followed by a discussion of the stability properties of strange stars in Section 3. Section 4 is devoted to the study of the phase transition scenario, which is fixed once the EOSs are chosen. We then discuss

the cooling processes of strange stars in Section 5, and the results of our calculation are presented in Section 6. We summarize in Section 7.

2 COLD EQUATION OF STATE FROM PERTURBATIVE QCD

Lattice QCD calculation of T_p is highly uncertain at high chemical potential, but the latest results (Allton et al. 2002) indicate, though with relatively large uncertainties at high chemical potential, that T_p drops from its zero density value of 140 MeV to about 50 MeV at 1.5 times nuclear matter density $\rho_0 = 0.17$ fm^{-3} and down to a few MeV for density a few times ρ_0. Some previous proto-neutron star evolution calculations indeed show that it is feasible to reach the phase transition in supernovae (Benvenuto & Lugones 1999). While there are still large uncertainties in both high-density QCD and the proto-neutron star evolution, we believe it is worthwhile studying the possible consequences of the QCD phase transition in supernovae. We assume a constant T_p in the star and present results for $T_p = 1$, 10 MeV for comparison. We adopt the simple picture that matter at temperature above (below) T_p is in the quark (hadronic) phase.

To study the properties of quark matter, various EOSs have been used. The MIT Bag model is most widely used due to its simple analytic form (Alcock et al. 1986). Here we follow Fraga, Pisarski & Schaffner-Bielich (2001) and use the EOS derived from perturbative QCD for cold, dense quark matter up to second order in the strong coupling constant α_s. α_s becomes small in the high density limit, with a value of about 0.4 in the relevant density regime. It turns out that this EOS is very similar to the MIT Bag model EOS, with an effective Bag constant Fraga et al. (2001), and we would have obtained basically the same results using the latter. None of our results in the cooling calculation depends on the validity of perturbative QCD in compact star regime.

All thermodynamic properties can be obtained from the thermodynamic potential $\Omega(\mu)$, where μ is the chemical potential. At zero quark mass limit, the number densities of u, d, s quarks are the same,

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and hence charge neutrality is automatically satisfied, without any need of electrons. The zero temperature perturbative QCD thermodynamic potential has been calculated up to order α_s^2 (Freedman & McLerran 1978; Baluni 1978) in the modified minimal subtraction scheme (Baluni 1978):

$$\Omega(\mu) = -\frac{N_f \mu^4}{4\pi^2}\left\{1 - 2\tilde{\alpha}_s - [G + N_f \ln \tilde{\alpha}_s + \beta_0 \ln \tilde{\Lambda}]\tilde{\alpha}_s^2\right\}, \quad (1)$$

where $\beta_0 = 11 - 2N_f/3$, N_f is the number of quark flavors, $G = G_0 + N_f(\ln N_f - 0.536)$, $G_0 = 10.374 \pm 0.13$, $\tilde{\alpha}_s \equiv \alpha_s/\pi$, $\tilde{\Lambda} \equiv \Lambda/\mu$, Λ being the renormalization subtraction point, and

$$\tilde{\alpha}_s(\Lambda) = \frac{4}{\beta_0 u}\left\{1 - \tilde{\beta}_1 \ln u + \tilde{\beta}_1^2\left[\left(\ln u - \frac{1}{2}\right)^2 + \tilde{\beta}_2 - \frac{5}{4}\right]\right\}, \quad (2)$$

with $u = \ln(\Lambda^2/\Lambda_{\overline{MS}}^2)$, $\Lambda_{\overline{MS}} = 365$ MeV, $\beta_1 = 51 - 19N_f/3$, $\beta_2 = 2857 - 325N_f^2/27$, $\tilde{\beta}_1 = 2\beta_1/\beta_0^2 u$ and $\tilde{\beta}_2 = \beta_2\beta_0/8\beta_1^2$. It is believed that $\tilde{\Lambda}$ lies in the range between 2 and 3 (Fraga et al. 2001). Both the first- and second-order terms decrease the pressure of the strange quark matter relative to the ideal gas. The pressure depends weakly on the strange quark mass m_s, changing only by less than 5 per cent for m_s up to 150 MeV (Wong & Chu 2003). We will therefore use the massless EOS in the calculation.

3 STABILITY OF STRANGE QUARK MATTER

The structure of a static, non-rotating and spherically symmetric strange star can be calculated by solving the Tolman–Oppenheimer–Volkov (TOV) equations together with the EOS (Glendenning 1996). A strange star can be stable even at zero temperature if its binding energy is larger than that of a neutron star with the same baryonic mass, which is indeed the case for $\tilde{\Lambda}$ around 2.7 (see Table 1), for several commonly used neutron star EOSs (Weber

Table 1. Total conversion energy E_{conv} for various $\tilde{\Lambda}$. A neutron star gravitational mass $M_G(NS) = 1.4$ $M_\odot$ is assumed, and the baryonic masses of strange stars are chosen to equal those of the neutron stars. The many-body approximation for HV, HFV, $\Lambda_{BroB}^{RBHF} + $ HFV and G_{M78}^{K240} EOSs are relativistic Hartree, relativistic Hartree–Fock, relativistic Brueckner–Hartree–Fock + relativistic Hartree–Fock and relativistic Hartree respectively (Weber 1999).

EOS(NS)	$M_B/M_\odot$	$\tilde{\Lambda}$	$M_G(SS)/M_\odot$	$E_{conv}/10^{53}$ erg
HV	1.51	2.473	1.44	+0.72
		2.600	1.41	+0.18
		2.880	1.33	−1.25
		3.000	1.29	−1.97
HFV	1.60	2.473	1.516	+2.08
		2.600	1.478	+1.40
		2.880	1.400	0
		3.000	1.363	−0.66
Λ_{BroB}^{RBHF}+HFV	1.62	2.473	/	/
		2.600	1.50	+1.79
		2.880	1.41	+0.18
		3.000	1.38	−0.36
G_{M78}^{K240}	1.56	2.473	1.48	+1.43
		2.600	1.45	+0.90
		2.880	1.37	−0.54
		3.000	1.33	−1.25

1999). We are however interested in the possibility that strange quark matter is only stable for $T > T_p$, and so we choose a $\tilde{\Lambda} < 2.7$, so that when the hot strange star cools to low temperature, it will convert to a neutron star. For $\tilde{\Lambda} = 2.473$, the maximum gravitational mass is 1.516 $M_\odot$ with a baryonic mass of 1.60 $M_\odot$ and radius 8.54 km. We will use this set of parameters in the calculation of the cooling behaviour because the maximum mass is close to observational data of compact stars. In fact, we have also used other values of $\tilde{\Lambda}$, and the cooling behaviour is qualitatively similar, as long as the star undergoes a phase transition.

4 PHASE TRANSITION FROM STRANGE STARS TO NEUTRON STARS

It has long been suggested that strange stars can be formed from a phase transition of neutron stars to strange stars due to an abrupt increase in density (Cheng & Dai 1996, 1998). However, from the theoretical point of view, formation of quark–gluon plasma is favoured when both temperature and chemical potential are high enough (Shuryak 1988). We propose that strange stars are formed in supernovae where both the temperature and density are high, with initial temperature (Petschek 1990) $T_i \sim 40$ MeV $> T_p$. The star then cools to T_p and hadronizes into a neutron star containing ordinary baryons. This is just the same scenario believed to occur in ultrarelativistic heavy-ion collisions (Shuryak 1988). If the baryonic mass M_B is conserved during the phase transition, the total conversion energy E_{conv} released is:

$$E_{conv} = [M_G(SS) - M_G(NS)]c^2, \quad (3)$$

where $M_G(SS)$ and $M_G(NS)$ are the gravitational masses of the strange star and neutron star respectively (Bombaci & Datta 2000). Whether a phase transition can occur and how much energy is released depend on both the EOSs of quark matter and nuclear matter. We choose several commonly used neutron star EOSs, $M_G = 1.40$ $M_\odot$ (Weber 1999), and the conversion energy for different $\tilde{\Lambda}$ are summarized in Table 1. For $\tilde{\Lambda} = 2.473$, typically 10^{53} erg is released during the conversion process, which depends only weakly on the nuclear matter EOS.

5 COOLING PROPERTIES

The surface of a newborn strange star is so hot that all the materials, other than quark matter, are evaporated leaving the strange star nearly bare without any crust (Usov 2001). Since the thermal conductivity of strange matter is high and the density profile of the strange star is very flat, we take the uniform temperature and density approximation. The strange star cools according to:

$$C_q \frac{dT}{dt} = -L_q, \quad (4)$$

where C_q is the total heat capacity of all the species in quark matter, and L_q is the total luminosity of the star. When the temperature drops to T_p, the star undergoes a phase transition releasing a conversion energy E_{conv}.

During the phase transition, we assume that the quark and neutron matter are distributed uniformly and calculate the luminosity of the mixed phase by the weighted average of those of the quark matter and the neutron matter (Lattimer et al. 1991; Wong & Chu 2003). When the strange star has converted completely to a neutron star, it then follows the standard cooling of a neutron star with an initial temperature of T_p.

The detailed thermal evolution is governed by several energy transport equations. We adopt a simple model that a neutron star has a uniform temperature core with high conductivity and two layers of crust, the inner crust and the outer crust, which transport heat not as effectively as the core or quark matter. The typical thickness of the crust is ∼10 per cent of the radius, and we can use the parallel-plane approximation to describe the thermal evolution of the inner crust. The thermal history of the inner crust can be described by a heat conduction equation:

$$c_{\text{crust}} \frac{\partial T}{\partial t} = \frac{\partial}{\partial r} \left(K \frac{\partial T}{\partial r} \right) - \epsilon_\nu, \tag{5}$$

where c_{crust} is the specific heat of the inner crust, K is the effective thermal conductivity, and ϵ_ν is the neutrino emissivity. As a rule of thumb, the effective surface temperature T_e and the temperature at the interface of inner and outer crust, T_b, are related by (Gudmundsson, Pethick & Epstein 1983):

$$T_{\text{b8}} = 1.288 \left(T_{\text{s6}}^4 / g_{\text{s14}} \right)^{0.455}, \tag{6}$$

where g_{s14} is the surface gravity in units of 10^{14} cm s^{-2}, T_{b8} is the temperature between the inner and outer crusts in units of 10^8 K, and T_{s6} is the effective surface temperature in units of 10^6 K. The luminosity at the stellar surface, L_{surface}, is equal to the heat flux at the interface of inner and outer crusts:

$$-K \frac{\partial T}{\partial r} = L_{\text{surface}} / (4\pi R^2), \tag{7}$$

where R is the radius of the star. The boundary condition at the interface of the core and inner crust is

$$C_{\text{core}} \frac{\partial T}{\partial t} = -K \frac{\partial T}{\partial r} A_{\text{core}} - L_\nu^{\text{core}}, \tag{8}$$

where C_{core} is the total heat capacity of the core, A_{core} is the surface area of the core, and L_ν^{core} is the total neutrino luminosity of the core.

5.1 Heat capacity of quark stars

The total heat capacity is the sum of the heat capacities of all species in the star. Without the effect of superfluidity, the quark matter can be considered as a free Fermi gas, with a specific heat (Iwamoto 1980) $c_q = 2.5 \times 10^{20} \tilde{\rho}^{2/3} T_9$ erg cm^{-3} K^{-1}, where $\tilde{\rho}$ is the baryon density in units of ρ_0 and $T_9 \equiv T/10^9$ K. In the superfluid state, the specific heat is modified as (Horvath, Benvenuto & Vucetich 1991; Maxwell 1979)

$$c_q^{\text{sf}} = 3.15 c_q e^{-\frac{1.76}{\tilde{T}}} \left[\frac{2.5}{\tilde{T}} - 1.66 + 3.64\tilde{T} \right], \quad \text{for } \tilde{T} \leqslant 1, \tag{9}$$

where $\tilde{T} = T/T_c$, $k_B T_c = \Delta/1.76$, and Δ is the energy gap in MeV. It has been argued that for quark matter, even with unequal quark masses, in the Colour–Flavour Locked (CFL) phase in which all the three flavours and colours are paired, quark matter is automatically charge neutral and no electrons are required (Rajagopal & Wilczek 2001). However, for sufficiently large strange quark mass and the relatively low density regime near the star surface, the 2 colour–flavour SuperConductor (2SC) phase is preferred. Therefore, in a real strange star, electrons should be present. The contribution of electrons can be parametrized by the electron fraction Y_e which depends on the model of strange stars. We choose $Y_e = 0.001$ as a typical value. The specific heat capacity of electrons in the strange star is given by (Ng et al. 2003) $c_e = 1.7 \times 10^{20} (Y_e \tilde{\rho})^{2/3} T_9$ erg cm^{-3} K^{-1}, which is unaffected by the superfluidity of quark matter. Hence it

dominates the total heat capacity of the strange star when the temperature drops below ∼T_c.

5.2 Luminosity of quark stars

The total luminosity is the sum of all the energy emission mechanisms, including photon and neutrino emission. The dominating neutrino emission mechanism is the quark URCA process, with emissivity (Iwamoto 1980):

$$\epsilon_d \simeq 2.2 \times 10^{26} \alpha_s(\tilde{\rho}) Y_e^{1/3} T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1}, \tag{10}$$

and we have chosen $\alpha_s = 0.4$ as a constant value throughout the quark star. In the superfluid state, the neutrino emissivity is suppressed by a factor of $\exp(-\Delta/T)$.

It has been pointed out that the bare surface of a strange star is a powerful source of e$^+$e$^-$ pairs owing to the strong surface electric field (Usov 1998). We adopt the e$^+$e$^-$ pair luminosity given in (Usov 2001) for our calculation. We also include the thermal equilibrium and non-equilibrium blackbody radiation in our calculation using standard treatment (Alcock et al. 1986; Usov 2001); the contribution of the latter is small compared to other mechanisms at high temperature. Once the temperature drops, the cooling is dominated by the relatively low power non-equilibrium blackbody radiation, as long as the star is still in the quark phase.

5.3 Microphysics of the neutron star

There are many different models of neutron star cooling. We adopt the one described by Ng (Maxwell 1979; Ng et al. 2003). The neutrino emission mechanisms are the direct URCA processes (Lattimer et al. 1991), the electron-proton Coulomb scattering in the crust (Festa & Ruderman 1969), and the neutrino bremsstrahlung (Ng et al. 2003). The surface luminosity will be of the blackbody radiation $L_{\text{bb}} = 4\pi R^2 \sigma T_s^4$, with the effective surface temperature T_s. The blackbody radiation will be the dominating cooling mechanism after neutrino emissions are switched off.

For the thermal conductivity of the inner crust K, we use a temperature dependent model (Lindblom, Owen & Ushomirsky 2000), $K = 2.8 \times 10^{21}/T_9$ erg cm^{-1} s^{-1} K^{-1}. The choice of K will not be important after the epoch of thermal relaxation, which is of the order 10–100 yr. The temperature of the inner crust and the core will be uniform after that.

When a strange star is born just after the stellar collapse, its temperature is very high, of the order 10^{11} K (Petschek 1990). $\tilde{\Lambda}$ mainly affects the conversion energy, which affects the duration of the phase transition. The cooling mechanisms depend only weakly on $\tilde{\Lambda}$ while the cooling curves depend weakly on T_i. We assume $T_i = 40$ MeV for our calculations. We choose a gap value $\Delta = 100$ MeV (Ng et al. 2003) to describe the superfluidity phase of quark matter, and we have checked that using $\Delta = 1$ MeV gives qualitatively similar results (Wong & Chu 2003).

6 RESULTS

The observables are the luminosity and the surface temperature at infinity, L^∞ and T_s^∞, which are related to the stellar surface values, L and T_s (Tsuruta et al. 2002): $T_s^\infty = e^{\phi_s} T_s$, $L^\infty = e^{2\phi_s} L$, where $e^{\phi_s} = \sqrt{1 - 2M_G/R}$ is the gravitational redshift at the stellar surface. The various cooling curves (solid lines) for $T_p = 1$ (10) MeV are shown in left (right) panels of Fig. 1.

For a large range of parameter values and nuclear matter EOSs, we obtain a large energy released, of order 10^{53} erg. The duration of
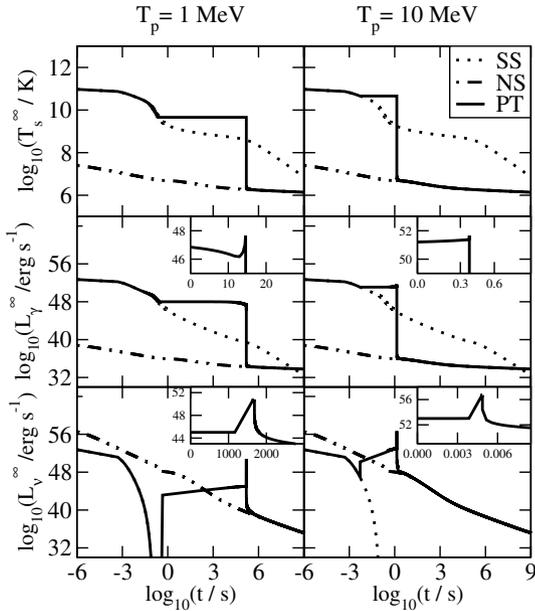
Figure 1. Cooling curves corresponding to two different models. Left (right) panels are for models with small (large) phase transition temperature $T_p = 1$ (10) MeV. The dotted (dashed) lines are the cooling curves of a pure strange (neutron) star without phase transition. The solid line represents the scenario with phase transition. T_s^∞, L_γ^∞ and L_ν^∞ denote surface temperature, photon luminosity and neutrino luminosity respectively. $T_i = 40$ MeV and $\Delta = 100$ MeV are assumed. The small insets indicate the peak luminosities for models with phase transition (PT). The time axes of the small insets of the upper left, lower left, upper right and lower right start at $t = 155\,670$, $155\,400$, 1 and 1.369 s respectively.

this energy release depends sensitively on T_p; a higher T_p results in a higher luminosity and shorter phase transition duration. It can be as short as seconds for $T_p = 10$ MeV, or as long as hundred thousands of seconds for $T_p = 1$ MeV. The surface temperature of the star drops rapidly (top panels of Fig. 1), reaching 10^7 K already within the first second ($T_p = 10$ MeV) to first hundred thousand seconds ($T_p = 1$ MeV). The decrease in surface temperature is particularly drastic at the completion of the conversion, which is a unique feature of the phase transition not seen in either a pure strange star (dotted curves) or a pure neutron star (dot–dashed curves).

The photon luminosity (middle panels in Fig. 1) is initially dominated by the e^+e^- pair emission mechanism and is large in the quark phase due to the strong surface electrostatic field. Since the e^+e^- pairs are not affected by the superfluidity gap, the photon luminosity is hardly affected by the gap values. The total energy radiated by e^+e^- pair emission is $4.24 \times 10^{50} (1.47 \times 10^{53})$ erg for $T_p = 10(1)$ MeV. Once the phase transition is completed, the surface field of a neutron star is much weaker and this mechanism is turned off. The photon luminosity therefore drops by over ten orders of magnitudes, and this is more drastic for larger T_p, because the phase transition occurs earlier and with shorter duration.

A distinct second burst of neutrinos shows up in the neutrino luminosity (bottom panels of Fig. 1), which accompanies the completion of the phase transition and arises because of the higher neutrino emissivity in neutron matter. For $T_p = 10$ MeV, the neutrino flux rises by over ten orders of magnitudes within a small fraction of a second. Note that we have not incorporated a detailed transport calculation for the neutrinos, which results in a broadening of the neutrino bursts we present here. Indeed, for $T_p = 10$ MeV, the peak

neutrino intensity of about 10^{56} erg s^{-1} lasts only for 10^{-3} s, and these neutrinos will be spread out over a diffusion time-scale of ($\sim$1–10 s) (Petschek 1990), reducing the peak intensity by a factor of 10^3. The first and second neutrino peaks are likely rendered indistinguishable by the relatively slow neutrino diffusion out of the dense medium. A much more careful treatment of the neutrino transport is clearly needed here (Liebendörfer et al. 2004). However, if T_p is as low as 1 MeV, the two bursts of similar flux can be separated by as long as 10^5 s, which should be observable by modern neutrino observatories. The two neutrino bursts can in principle be distinguished also by their energy spectra. The first burst is emitted near the initial high temperature of the newborn strange star, while the second burst is associated with the phase transition temperature T_p, and therefore the second neutrino burst has a softer energy spectrum. The total energy radiated in neutrino is $3.15(1.27) \times 10^{53}$ erg for $T_p = 10(1)$ MeV.

This scenario of a second burst of neutrinos can be compared with two previous similar proposals (Benvenuto & Lugones 1999; Aguilera, Blaschke & Grigorian 2004). In our model, the burst is due to the phase transition from a quark star to a neutron star, which has a higher neutrino emissivity, whereas in previous proposals, the second burst accompanies the phase transition from a neutron star to a quark star. In Benvenuto's theory, the phase transition is delayed by a few seconds after the core bounce due to the presence of the neutrinos (Benvenuto & Lugones 1999). In Aguilera et al.'s theory (Aguilera et al. 2004), the burst is due to the initial trapping of neutrinos when the temperature is high and their sudden release when the quark star cools. If quark matter is not as stable as nuclear matter at low temperature, then there should be yet another phase transition back to nuclear matter, which is what we focus on, and the 'second' neutrino burst we proposed is then the 'third' neutrino burst.

If multiple neutrino bursts are observed, as may indeed be the case for the Kamiokande data for SN1987A (Hirata et al. 1987), whether the compact star changes from the quark phase to neutron phase (our model) or the other way around can be distinguished observationally in at least two ways. First, our model predicts that the cooling is much faster *before* the phase transition, but it will become slower *after* it. Secondly, the size of the post-phase-transition compact star, being a normal neutron star, would be larger in our model.

7 DISCUSSION AND CONCLUSION

Based on the lattice QCD phase diagram, we propose that the newborn compact star in a supernova is a strange star and it transforms to a neutron star when it cools down to a critical temperature T_p. The conversion energy can be of the order 10^{53} erg and is adequate to supply energy for gamma-ray bursts. The strange star cools rapidly owing to neutrino and e^+e^- emission, and its surface temperature drops drastically at the completion of the conversion, when a second neutrino burst emerges due to the higher neutrino emissivity of neutron matter. In our models, the phase transition is treated in a simplified manner. Hydrodynamic calculation is needed for a detailed description of the process starting from a supernova explosion. Here we discuss semi-quantitatively the signatures left by the quark to hadron phase transition, if it occurs in supernovae.

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