The observational appearance of strange stars

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1 Introduction

Strange stars that are entirely made of strange quark matter (SQM) have been long ago proposed as an alternative to neutron stars (e.g., [1, 2]). The possible existence of strange stars is a direct consequence of the conjecture that SQM composed of roughly equal numbers of up, down, and strange quarks plus a smaller numbers of electrons (to neutralize the electric charge of the quarks) may be the absolute ground state of the strong interaction, i.e., absolutely stable with respect to ^{56}Fe [1, 3]. The bulk properties (size, moment of inertia, etc.) of models of strange and neutron stars in the observed mass range ($1 < M/M_\odot < 2$) are rather similar, and it is very difficult to discriminate between strange and neutron stars [4].

SQM with the density of $\sim 5 \times 10^{14}$ g cm^{-3} might exist up to the surface of strange stars [2, 4]. Such a bare strange star differs qualitatively from a neutron star which has the density at the stellar surface (more exactly at the stellar photosphere) of about $0.1 - 1$ g cm^{-3}. This opens observational possibilities to distinguish bare strange stars from neutron stars.

2 Thermal emission from bare strange stars

At the bare SQM surface of a strange star the density changes abruptly from $\sim 5\times10^{14}$ g cm^{-3} to zero. The thickness of the SQM surface is about 1 fm $= 10^{-13}$ cm, which is a typical strong interaction length scale. Since SQM at the surface of a bare strange star is bound via strong interaction rather than gravity, such a star is not subject to the Eddington limit in contrast to a neutron star [2, 5]. Below, we discuss the thermal emission of photons and e^+e^- pairs from the SQM surface of a hot bare strange star.

2.1 Emission of photons

Hot SQM is filled with electromagnetic waves in thermodynamic equilibrium with quarks. The dispersion relation of these waves may be written in the following simple form $\omega^2 = \omega_{\rm p}^2 + k^2c^2$, where ω is the frequency of electromagnetic waves, k is their wavenumber, and $\omega_{\rm p}$ is the plasma frequency of quarks [2]. This equation is the familiar dispersion relation for a plasma, and its conventional interpretation may be applied to SQM. Propagating modes exist only for $\omega > \omega_{\rm p}$. Therefore, there is the lower limit on the energy of electromagnetic photons that are in thermodynamic equilibrium with quarks, $\varepsilon_\gamma = \hbar\omega > \hbar\omega_{\rm p} \simeq 18.5(n_{\rm b}/n_0)^{1/3}$ MeV, where $n_{\rm b}$ is the baryon number density of SQM, and $n_0 = 0.17$ fm^{-3} is normal nuclear matter density. At the SQM surface where the pressure is zero, we expect $n_{\rm b} \simeq (1.5-2)n_0$ and $\hbar\omega_{\rm p} \simeq 20-25$ MeV. i.e., the spectrum of thermal equilibrium photons radiated from the bare SQM surfaces of strange stars is very hard, $\varepsilon_\gamma > \hbar\omega_{\rm p} \simeq 20-25$ MeV [2].

The energy flux emitted from the unit surface of SQM in thermal equilibrium photons is [5, 6]

$$F_{\rm eq} = \frac{\hbar}{c^2}\int_{\omega_{\rm p}}^{\infty} d\omega\,\frac{\omega\,(\omega^2-\omega_{\rm p}^2)\,g(\omega)}{\exp\left(\hbar\omega/k_{\rm B}T_{\rm S}\right)-1}\,, \tag{1}$$

where

$$g(\omega) = \frac{1}{2\pi^2}\int_0^{\pi/2} d\vartheta\,\sin\vartheta\,\cos\vartheta\,D(\omega,\vartheta)\,, \tag{2}$$

$k_{\rm B}$ is the Boltzmann constant, $T_{\rm S}$ is the surface temperature, $D(\omega,\vartheta)$ is the coefficient of radiation transmission from SQM to vacuum, $D = 1-(R_\perp + R_\|)/2$, and

$$R_\perp = \frac{\sin^2(\vartheta-\vartheta_0)}{\sin^2(\vartheta+\vartheta_0)}\,,\quad R_\| = \frac{\tan^2(\vartheta-\vartheta_0)}{\tan^2(\vartheta+\vartheta_0)}\,,\quad \vartheta_0 = \arcsin\left[\sin\vartheta\sqrt{1-\left(\frac{\omega_{\rm p}}{\omega}\right)^2}\,\right]. \tag{3}$$

Figure 1 shows the ratio of the equilibrium photon emissivity of the bare SQM surface to the blackbody surface emissivity, $\xi_{\rm eq} = F_{\rm eq}/F_{\rm BB}$, where $F_{\rm BB} = \sigma T_{\rm S}^4$, and σ is the Stefan-Boltzmann constant. From Figure 1 we can see that at $T_{\rm S} \ll \hbar\omega_{\rm p}/k_{\rm B} \sim 10^{11}$ K the equilibrium photon radiation from the bare surface of a strange star is very small, compared to the blackbody one.

Low energy photons ($\varepsilon_\gamma < \hbar\omega_{\rm p}$) may leave SQM if they are produced by a non-equilibrium process in the surface layer with the thickness of $\sim c/\omega_{\rm p} \simeq 10^{-12}$ cm. The upper limit on the emissivity of SQM in non-equilibrium photons at low energies is $\xi_{\rm neq} = F_{\rm neq}/F_{\rm BB} \leq 10^{-4}$ [6].

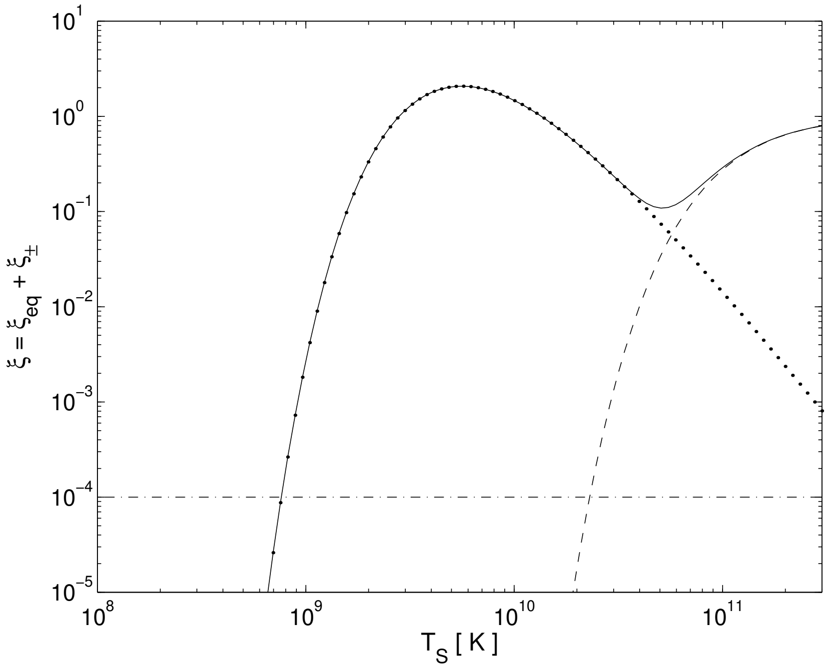

Figure 1: Total emissivity of bare SQM surface (solid line), which is the sum of emissivities in equilibrium photons (dashed line) and e^+e^- pairs (dotted line), divided by the blackbody emissivity, $\xi = \xi_{\rm eq} + \xi_{\pm}$. The value of ξ is valid at least for the surface temperature $T_{\rm S} \geq 8 \times 10^8$ K when ξ is more than the upper limit on $\xi_{\rm neq}$, $\xi_{\rm neq} \leq 10^{-4}$, which is shown by the dot-dashed line.

2.2 Emission of e^+e^- pairs

It was pointed out [7] that the bare surface of a hot strange star may be a powerful source of e^+e^- pairs which are created in an extremely strong electric field at the quark surface and flow away from the star. The electric field is generated because there are electrons with the density $n_{\rm e} \simeq (10^{-3} - 10^{-4})n_{\rm b}$ in SQM to neutralize the electric charge of the quarks (e.g., [2, 4]). The point is that the electrons, being bound to SQM by the electromagnetic interaction alone, are able to move freely across the SQM surface, but clearly cannot move to infinity because of the bulk electrostatic attraction to the quarks. The electron distribution extends up to $\sim 10^3$ fm above the quark surface, and a strong electric field is generated in the surface layer to prevent the electrons from escaping to infinity, counterbalancing the degeneracy and thermal pressure. The typical magnitude of the electric field at the SQM surface is $\sim 5 \times 10^{17}$ V cm^{-1} [2]. This field is a few ten times higher than the critical field $E_{\rm cr} = m^2c^3/e\hbar \simeq 1.3 \times 10^{16}$ V cm^{-1} at which vacuum is unstable to creation of e^+e^- pairs. In such a strong electric field, $E \gg E_{\rm cr}$, in vacuum, the pair creation rate is extremely high, $W_\pm \simeq 1.7\times10^{50}(E/E_{\rm cr})^2$ cm^{-3} s^{-1}. At $E \simeq 5\times10^{17}$ V cm^{-1}, we have $W_\pm \simeq 2.5\times10^{53}$ cm^{-3} s^{-1}. The high-electric-field region is, however, not a vacuum. The electrons present fill up states into which would-be-created electrons have to go. This reduces the pair-creation rate from the vacuum value. At zero temperature the process of pair creation is suppressed altogether because there is no free levels for electrons to be created [7].

At finite temperatures, $T_{\rm S} > 0$, in thermodynamical equilibrium electronic states are only partly filled, and pair creation by the Coulomb barrier becomes possible. Since the rate of pair production when electrons are created into the empty states is extremely high, the empty states below the pair creation threshold, $\varepsilon \le \varepsilon_{\rm F} - 2m_{\rm e}c^2$, are occupied by created electrons almost instantly, where $\varepsilon_{\rm F} = \hbar c(\pi^2 n_{\rm e})^{1/3} \simeq 20$ MeV is the Fermi energy of electrons in SQM, and $m_{\rm e}$ is the electron mass [7]. Then, the rate of pair creation by the Coulomb barrier is determined by the process of thermalization of electrons which favors the empty-state production below the pair creation threshold. The thermal energy of SQM is, in fact, the source of energy for the process of pair creation.

The flux of e^+e^- pairs from the unit surface of SQM is [5]

$$f_\pm \simeq 10^{39}\left(\frac{T_{\rm S}}{10^9\ {\rm K}}\right)^3 \exp\left[-11.9\left(\frac{T_{\rm S}}{10^9\ {\rm K}}\right)^{-1}\right] J(\zeta)\ \ {\rm cm^{-2}\,s^{-1}}\,, \tag{4}$$

where

$$J(\zeta) = \frac{1}{3}\frac{\zeta^3\ln(1+2\zeta^{-1})}{(1+0.074\zeta)^3} + \frac{\pi^5}{6}\frac{\zeta^4}{(13.9+\zeta)^4}\,, \qquad \zeta = 2\sqrt{\frac{\alpha}{\pi}}\frac{\varepsilon_{\rm F}}{kT_{\rm S}} \simeq 0.1\frac{\varepsilon_{\rm F}}{kT_{\rm S}}\,, \tag{5}$$

and $\alpha = e^2/\hbar c = 1/137$ is the fine structure constant.

The energy flux from the unit surface of SQM in e^+e^- pairs created by the Coulomb barrier is $F_\pm \simeq \varepsilon_\pm f_\pm$, where $\varepsilon_\pm \simeq m_{\rm e}c^2 + k_{\rm B}T_{\rm S}$ is the mean energy of created particles [7]. Figure 1 shows the ratio of the SQM surface emissivity in e^+e^- pairs to the blackbody surface emissivity, $\xi_\pm = F_\pm/F_{\rm BB}$, versus the surface temperature $T_{\rm S}$. Creation of e^+e^- pairs by the Coulomb barrier is the main mechanism of thermal emission from the surface of SQM at $8\times10^8 < T_{\rm S} < 5\times10^{10}$ K, while the equilibrium radiation dominates at extremely high temperatures, $T_{\rm S} > 5\times10^{10}$ K.

2.3 The thermal luminosity of a hot bare strange star

At $T_{\rm S} > 8\times10^8$ K, when the thermal emission from the SQM surface in both equilibrium photons and e^+e^- pairs prevail, the total thermal luminosity of a bare strange star is

$$L = L_{\rm eq} + L_\pm = 4\pi R^2 (F_{\rm eq} + F_\pm)\,, \tag{6}$$

where $R \simeq 10^6$ cm is the radius of the strange star. Figure 2 shows the value of L as a function of the surface temperature $T_{\rm S}$.

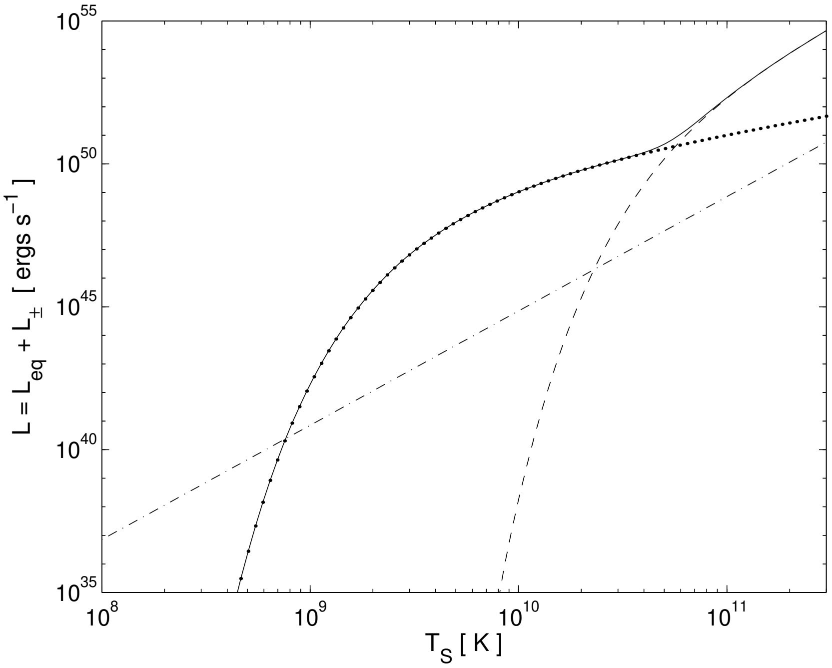

Figure 2: The total luminosity of a bare strange star $L = L_{\rm eq} + L_\pm$ (solid line), where $L_{\rm eq}$ and $L_\pm$ are the luminosities in thermal equilibrium photons (dashed line) and e^+e^- pairs (dotted line), respectively. The upper limit on the luminosity in non-equilibrium photons, $L_{\rm neq} < 10^{-4} 4\pi R^2 F_{\rm BB}$, is shown by the dot-dashed line.

At $T_{\rm S} > 8 \times 10^8$ K the luminosity in e^+e^- pairs created by the Coulomb barrier at the SQM surface is very high, $L_\pm > 10^{40}$ ergs s^{-1} (see Fig. 2), that is at least four orders of magnitude higher than

$$L_\pm^{\rm max} \simeq 4\pi m_{\rm e} c^3 R/\sigma_{\rm T} \simeq 10^{36} \text{ ergs s}^{-1}\,, \tag{7}$$

where $\sigma_{\rm T}$ is the Thomson cross-section. In this case, the time-scale $t_{\rm ann} \sim (n_\pm \sigma_{\rm T} c)^{-1}$ for annihilation of e^+e^- pairs is much shorter than the time-scale $t_{\rm esc} \sim R/c$ for their escape, $t_{\rm ann}/t_{\rm esc} \simeq L_\pm^{\rm max}/L_\pm < 10^{-4} \ll 1$, and e^+e^- pairs outflowing from the stellar surface mostly annihilate in the vicinity of the strange star, $r \sim R$ (e.g., [8]). The luminosity in e^+e^- pairs at the distance $r \gg R$ cannot be significantly more than $L_\pm^{\rm max}$. Therefore, far from a bare strange star with the surface temperature

$T_{\rm s} > 8 \times 10^8$ K the photon luminosity dominates irrespective of $T_{\rm s}$ and practically coincides with the total luminosity given by equation (6). At $T_{\rm s} < 8 \times 10^8$ K the total luminosity $L = L_{\pm} + L_{\rm neq}$ is somewhere between $\sim 4\pi 10^{-4} R^2 F_{\rm BB}$ and $\sim L_{\pm}$.

Till now, we assumed tacitly that SQM at the surface of the strange star is in the normal (nonsuperconducting) state. Recently, it was argued that SQM may be a color superconductor if its temperature is below some critical value (for a review, see [9]). In the classic BCS model, the critical temperature is $T_c \simeq 0.57\Delta_0/k_{\rm B}$, where Δ_0 is the energy gap at zero temperature. The value of Δ_0 is in the range from $\sim 0.1 - 1$ MeV [10] to $\sim 50 - 10^2$ MeV [9]. Color superconductivity can suppress the nonequilibrium radiation discussed in [6] significantly (if not completely). In this case, equation (6) may be used at $T_{\rm s} < 8 \times 10^8$ K as well. If SQM at the stellar surface is a color superconductor in the color-flavor locked (CFL) phase the process of e^+e^- pair creation at the SQM surface may be turned off at $T \ll T_c$. This is because cold SQM in the CFL phase is electrically neutral, and no electrons are required and none are admitted inside CFL quark matter [11].

The energy spectrum of photons far from the strange star depends on the total thermal luminosity. At $L > 10^{43}$ ergs s^{-1}, the photon spectrum is nearly blackbody with the temperature $T \simeq T_0(L/10^{43}$ ergs s$^{-1})^{1/4}$, where $T_0 \simeq 2 \times 10^8$ K [16]. For intermediate luminosities, $10^{42} < L < 10^{43}$ ergs s^{-1}, the effective temperature of photons is more or less constant, $T \sim T_0$ [17]. At $L_{\rm th} < 10^{42}$ ergs s^{-1}, the hardness of the photon spectrum increases when L decreases. This is because photons that form in annihilation of e^+e^- pairs cannot reach thermodynamical equilibrium before they escape from the strange star vicinity. When the photon luminosity decreases from $\sim 10^{42}$ ergs s^{-1} to $\sim 10^{36}$ ergs s^{-1}, the mean energy of photons increases from ~ 100 keV to ~ 500 keV while the spectrum of photons changes eventually into a very wide ($\Delta E/E \sim 0.3$) annihilation line of energy $E \sim 500$ keV [17]. Such a behavior of photon spectra offers a good observational signature of hot bare strange stars. Super-Eddington luminosities are another finger print of such stars.

3 Thermal emission from non-bare strange stars

"Normal" matter (ions and electrons) may be at the quark surface of strange stars. The ions in the inner layer are supported against the gravitational attraction to the underlying strange star by a very strong electric field of the Coulomb barrier. There is an upper limit to the amount of normal matter at the quark surface, $\Delta M \leq 10^{-5} M_\odot$ [2, 12]. Such a massive envelope of normal matter with $\Delta M \sim 10^{-5} M_\odot$ completely obscures the quark surface. However, a strange star at the moment of its formation is very hot. The temperature in the interior of a nascent strange star is expected to be as high as a few $\times 10^{11}$ K [13]. The rate of mass ejection from an envelope of such a hot strange star is very high [14]. Besides, the high surface temperature leads to a considerable reduction of the Coulomb barrier, which favors the tunneling of nuclei toward the quark surface [15]. Therefore, it is natural to expect that in a few seconds after formation of a strange star the normal-matter envelope is either blown away by radiation pressure or quarkonized, and the stellar surface is completely bare. The SQM surface remains bare until the thermal luminosity of the strange star is more than the Eddington limit, $L > L_{\rm Edd} \simeq 1.3\times 10^{38}(M/M_\odot)$ ergs s^{-1}.

3.1 Low-mass normal-matter atmospheres

At $L < L_{\rm Edd}$ the normal-matter atmosphere forms because of gas accretion onto the strange star. The presence of the atmosphere may restore the ability of the stellar surface to radiate soft photons (this is like painting with black paint on a silver surface).

The strange star acts on the atmosphere as a heat reservoir. At $T_{\rm s} > 10^7$ K when the hot gas emits mainly due to bremsstrahlung radiation, the thermal structure of the low-mass normal-matter atmosphere and its photon radiation were considered in [18] by solving the heat transfer problem with $T = T_{\rm s}$ as a boundary condition at the inner layer. It was shown that if the atmosphere mass ΔM is smaller than

$$\Delta M_1 \simeq 7\times 10^{11}\frac{A}{Z^2}\left(\frac{T_{\rm s}}{10^8\,{\rm K}}\right)^{3/2}\left(\frac{R}{10^6\,{\rm cm}}\right)^2\ {\rm g}\,, \tag{8}$$

the atmosphere is nearly isothermal, and its photon luminosity is

$$L_{\rm a} \simeq \frac{4\times 10^{33}Z^3}{A(1+Z)}\left(\frac{R}{10^6\,{\rm cm}}\right)^{-4}\left(\frac{M}{M_\odot}\right)\left(\frac{T_{\rm s}}{10^8\,{\rm K}}\right)^{-1/2}\left(\frac{\Delta M}{10^{12}\,{\rm g}}\right)^2\ {\rm ergs\ s^{-1}}\,, \tag{9}$$

where A is the mass number of ions and Z is their electrical charge.

At $\Delta M_1 < \Delta M < \Delta M_2$, convection develops in the atmosphere, and the photon luminosity is $\tilde{L}_{\rm a} = 4\gamma L_{\rm a}/(3\gamma+1)$, where

$$\Delta M_2 \simeq \frac{4\times 10^{12}A}{Z^2\mu^{1/2}}\left(\frac{T_{\rm s}}{10^8\,{\rm K}}\right)\left(\frac{R}{10^6\,{\rm cm}}\right)^2\ {\rm g}\,, \tag{10}$$

μ=$A/(1+Z)$ is the mean molecular weight, and γ is the ratio of the specific heats at constant pressure and at constant volume [18]. For a rarefied totally-ionized plasma we have $\gamma = 5/3$ and $\tilde{L}_{\rm a} = (10/9)L_{\rm a}$. The difference between L and $\tilde{L}$ is within the accuracy of our calculations which is $\sim 20\%$.

At $\Delta M > \Delta M_2$, both thermal conductivity and convection are not able to account for the cooling of atmospheric matter, and a thermal instability develops in the atmosphere [18]. As a result, the atmosphere cannot be in hydrostatic equilibrium during a time larger than the characteristic cooling time, and it has to be strongly variable on a timescale of $\sim (10^{-4} - 10^{-3})(T_{\rm S}/10^8\,{\rm K})^{1/2}$ s. This variability of the strange-star atmosphere and its photon luminosity are known poor. Most probably, at $\Delta M > \Delta M_2$ the tendency of the photon luminosity to increase with increase of ΔM holds up to $L_{\rm a} \simeq L_{\rm Edd}$ if $T_{\rm S} > 3 \times 10^7$ K [18].

The photon emission from the low-mass normal-matter atmosphere of a hot ($T_{\rm S} > 3 \times 10^7$ K) strange star is hard. The spectrum of this emission is similar to the spectrum of thermal emission of optically thin plasma at $k_{\rm B}T$ up to $\sim 10^2$ keV [18]. This differs significantly from the photon emission of neutron stars.

3.2 Massive normal-matter envelopes with $\Delta M \sim 10^{-5} M_\odot$

If the age of a neutron star is $t > 10^2$ yr, the stellar interior may be divided into two regions: the isothermal core with density $\rho > \rho_e \sim 10^{11}$ g cm^{-3} and the outer envelope with $\rho < \rho_e$ (e.g., [19]). Since the density of the normal-matter envelope with $\Delta M \sim 10^{-5} M_\odot$ at the quark surface of a strange star is about ρ_e, the temperature variation between the quark surface and the surface of the normal-matter envelope is more or less the same as the core-to-surface temperature variation of a neutron star for a fixed temperature at the stellar center. The cooling behavior of the quark core of strange stars depends on many factors and may be more or less similar to the cooling behavior of the isothermal core of neutron stars [20]. Therefore, from observations of thermal X-ray emission from not too young ($t > 10^2$ yr) compact objects it is difficult to distinguish strange stars with massive ($\Delta M \sim 10^{-5} M_\odot$) normal-matter envelopes from neutron stars (cf. [21]).

4 Soft γ-ray repeaters may be bare strange stars

Bare strange stars can radiate at the luminosities greatly exceeding the Eddington limit (see §2). The mean energy of radiated photons is a few ten keV or higher. Therefore, bare strange stars are reasonable candidates for soft γ-ray repeaters (SGRs) that are the sources of brief (~ 0.1 s), intense [$\sim (10^3 - 10^4) L_{\rm Edd}$] outbursts with soft γ-ray spectra (for a review on SGRs, see [22]). The bursting activity of SGRs may be explained by fast heating of the SQM surface of bare strange stars up to the temperature of $\sim (1-2) \times 10^9$ K (see Fig. 2) and its subsequent thermal emission [5, 23]. The heating mechanism may be either impacts of comets onto bare strange stars [23, 24] or fast decay of superstrong ($\sim 10^{14} - 10^{15}$ G) magnetic fields [25].

Two giant flares were observed on 5 March 1979 and 27 August 1998 from SGR 0526-66 and SGR 1900+14, respectively. The peak luminosity of these remarkable flares was as high as $\sim 10^{45}$ ergs s^{-1}, 7 orders of magnitude in excess of the Eddington limit for a solar-mass object [26]. This luminosity is about ten times higher than the luminosity of our Galaxy. Recently, it was shown that the light curves of the two giant outbursts may be easily explained in the following model [23]. A comet-like object with the mass $M_c \sim 10^{25}$ g falls onto a bare strange star. The total duration of the accretion is $\Delta t \sim 10^2 - 10^3$ s. The accreted matter sinks into the strange star and quarkonizes [2]. During the accretion, $t < \Delta t$, the surface layers of the strange star are heated, while their thermal radiation is completely suppressed by the falling matter. The total thermal energy accumulated in the surface layers at the moment $t = \Delta t$ is $Q \simeq 0.1 M_c c^2 \sim 10^{45}$ ergs. When the accretion is finished and the strange star vicinity is transparent for radiation, some part of the energy Q is emitted from the quark surface and observed as a giant burst. Figure 3 shows the light curve expected in this model for $Q = 9.2 \times 10^{44}$ ergs and $\Delta t = 370$ s [23]. This light curve is in good agreement with the light curve observed for the 5 March 1979 event [26]. The spectrum of this event may be also explained by the thermal emission from the strange star [17].

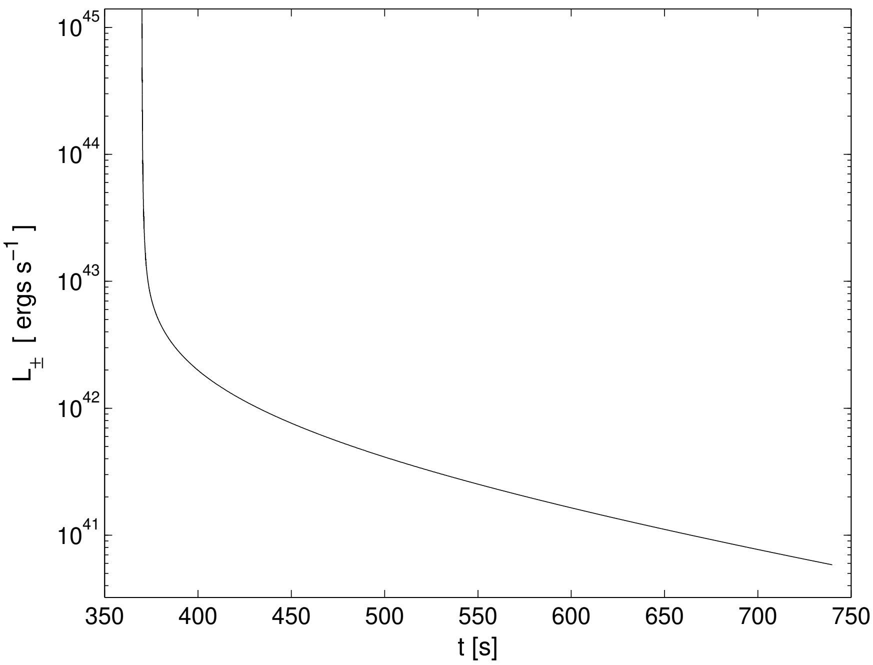

Figure 3: The light curve expected for $Q = 9.2 \times 10^{44}$ ergs and $\Delta t = 370$ s.

The light curve of the 27 August 1998 event may be fitted fairly well in our model for $Q = 6.4 \times 10^{44}$ ergs and $\Delta t = 270$ s [23].

One of the sources of matter that falls onto a strange star producing a SGR could be debris formed in collisions of planets orbiting the star in nearly coplanar orbits [27]. In this particular model, there appear two typical masses ($\sim 10^{25}$ g and $\sim 10^{22}$ g) available for prompt infall. Accretion of comet-like objects with the masses of $\sim 10^{25}$ g and $\sim 10^{22}$ g may result in the giant and typical flares of SGRs, respectively.

It is worth to note that the distribution of temperature in the surface layers at the moment $t = \Delta t$, when the accretion is just finished and the powerful radiation from the stellar surface just starts, completely determines the subsequent radiation from the strange star at $t \geq \Delta t$. If the surface layers of a bare strange star are heated very fast ($< 10^{-3}$ s) to this temperature distribution by any other mechanism, for example by decay of superstrong ($\sim 10^{14} - 10^{15}$ G) magnetic fields [25], the light curve of the subsequent radiation coincides with the light curve shown by Figures 3.

Recently, the response of a bare strange star to the energy input onto the stellar surface was studied numerically [28]. In these simulations, the energy input started at the moment $t = 0$, and it was spherical and steady at $t \geq 0$. A wide range of the rate of the energy input was considered, 10^{38} ergs s$^{-1} \leq L_{\rm input} \leq 10^{45}$ ergs s^{-1}. The rise time of the thermal radiation from the strange star was calculated for both normal and superconducting SQM. For giant outbursts ($L_{\rm input} \sim 10^{45}$ ergs s^{-1}), the rise time is $< 10^{-3}$ s irrespective of whether SQM is a superconductor or not. This time is consistent with available data on the two giant outbursts. For typical outbursts ($L_{\rm input} \sim 10^{41} - 10^{42}$ ergs s^{-1}) the rise time is $\sim 10^{2} - 10^{4}$ s for SQM in the normal state and $\sim 10^{-1} - 10^{-3}$ s for SQM in the superconducting state with the energy gap $\Delta_0 \geq 1$ MeV. Therefore, for typical outbursts the observed rise times ($\sim 10^{-1}$–10^{-3} s) may be explained in our model only if SQM is a superconductor with the energy gap of more than ~ 1 MeV.

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Discussion

A. Thampan (IUCAA): Won't general relativity modify (qualitatively) the temperature profile (T versus x) that you have got?

Usov: The effects of general relativity do not change qualitatively the distribution of temperature in the surface layers of the strange star. These effects can lead only to rather small ($\sim 20\%$) corrections. In our calculations, the effects of general relativity were ignored because many input parameters (for example, the thermal emission from the SQM surface) are known within a factor of 2 or so.

D.K. Hong (Pusan National University): In the case of SQM, why the rise time does not change much as the energy gap changes a lot?

Usov: This is because when the energy gap is higher than about 1 MeV both the specific heat of the quark subsystem of SQM and its thermal conductivity are strongly suppressed. In this case, the heat transport is mostly determined by the electron subsystem, and it practically does not depend on the energy gap.

J.E. Horvath (Sao Paulo University): Did you attempt spectral comparisons of the model with the outburst of SGR 1900+14 Aug. 9? In that case the light curve has shown evidence for several periods $\sim$ fractions of a second. Is there any "natural" room for them in this model?

Usov: I have compared the theoretical and observed spectra for the 5 March 1979 outburst and found that they are consistent with each other. Since the spectra of other outbursts do not differ qualitatively, I think that these spectra may be explained as well. Our consideration of the short-time structure of the light curves is just started, and we have no even preliminary results yet.