Strange Star Heating Events as a Model for Giant Flares of Soft-Gamma-Ray Repeaters

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Two giant flares were observed on 5 March 1979 and 27 August 1998 from the soft γ-ray repeaters SGR 0526 − 66 and SGR 1900 + 14, respectively. The striking similarity between these remarkable bursts strongly implies a common nature. We show that the light curves of the giant bursts may be easily explained in the model where the burst radiation is produced by the bare quark surface of a strange star heated, for example, by impact of a massive cometlike object.

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I. *Introduction.*— Strange stars are astronomical compact objects which are entirely made of deconfined quarks. The possible existence of strange stars is a direct consequence of the conjecture by Witten [1] that strange quark matter (SQM) composed of roughly equal numbers of up, down, and strange quarks plus a small number 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. SQM has been studied in many papers (e.g., Ref. [2]), and it was shown that, with the uncertainties inherent in a nuclear-physics calculation, the existence of stable SQM is plausible. The bulk properties (size, moment of inertia, etc.) of models of strange and neutron stars in the observed mass range ($1 < M/M_\odot < 1.8$) are rather similar, and it is very difficult to discriminate between strange and neutron stars [3,4]. SQM with the density of $\sim 5 \times 10^{14}$ g cm^{-3} can exist, by hypothesis, up to the surface of strange stars [4,5]. 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 strange stars from neutron stars, if indeed the formers exist.

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 and can radiate at the luminosity greatly exceeding $L_{\rm Edd} \simeq 1.3 \times 10^{38}(M/M_\odot)$ ergs s^{-1} [5]. Therefore, bare strange stars are reasonable candidates for soft γ-ray repeaters (SGRs) that are the sources of flares with Super-Eddington luminosities, up to $\sim 10^{44}$–10^{45} ergs s^{-1}.

There are four known SGRs, three within our Galaxy (SGR 1900 + 14, SGR 1806 − 20, and SGR 1627 − 41) and one in the Large Magellanic Cloud (SGR 0526 − 66). SGRs appear to be associated with radio supernova remnants, indicating that they are young ($\lesssim 10^4$ yr). SGRs are characterized by their recurrent emission of brief ($\sim$0.1 s), intense [$(\sim 10^3$–$10^4)L_{\rm Edd}$] bursts with soft γ-ray spectra [6].

A remarkable flare was observed by nine satellites on 5 March 1979 [7]. It was the first burst recorded from SGR 0525 − 66. The location of SGR 0525 − 66 is consistent with a supernova remnant (N49) in the Large Magellanic Cloud. Assuming a distance of 50 kpc to the supernova remnant N49, the peak luminosity of the short ($\sim$0.25 s) initial pulse was $\sim 1.6 \times 10^{45}$ ergs s^{-1} [8], 7 orders of magnitude in excess of the Eddington limit for a solar-mass object. This luminosity is about 10 times higher than the luminosity of our Galaxy. After the initial pulse, the source was observed for at least 200 s and pulsated with an 8 s periodicity, which was inferred to be the rotational period of SGR 0526 − 66. Recently (27 August 1998), a giant burst was observed from SGR 1900 + 14 [9]. This burst is nearly a carbon copy of the 5 March 1979 event (see Table I).

The model where the source of the 5 March 1979 event is a strange star has been long ago proposed by Alcock, Farhi, and Olinto [10]. Later, a few other strange star models were developed for SGRs [11,12]. However, the light curves expected for bursts in all these models were never calculated because the thermal emission from the bare quark surface of a strange star was poorly known. Recently, the thermal emission of bare strange stars was considered [13,14], and it was shown that creation of e^+e^- pairs by the Coulomb barrier at the quark surface is the main mechanism of thermal emission from the surface of SQM at the temperature $T_S < 5 \times 10^{10}$ K. Created e^+e^- pairs mostly annihilate in the vicinity of the strange star into γ rays. In this Letter, using the results of [13,14] we show that the light curves of the two giant bursts may be easily explained in the model where the burst radiation is produced by the bare surfaces of strange stars heated up to $\sim 2 \times 10^9$ K by impacts of massive cometlike objects.

II. *The model.*— Imagine that a cometlike object with the mass $\Delta M \sim 10^{25}$ g falls onto a strange star. We assume that the comet matter accretes steadily and spherically. 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 [5]. 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 $Q \simeq 0.1 \Delta M c^2 \sim 10^{45}$ ergs. When the accretion is finished and the strange star vicinity is transparent for

TABLE I. Comparison of observed [8] and theoretical characteristics of the two giant bursts. The accuracy of the observational characteristics of the burst radiation is not higher than ~20%.

Giant outburst Distance	SGR 0526 − 66 5 March 1979 50 kpc		SGR 1900 + 14 27 August 1998 10 kpc	
	Observations	Theory	Observations	Theory
Accretion of matter				
Duration Δt, s		370		280
Energy release Q, ergs		9.2×10^{44}		5.4×10^{44}
Initial pulse				
Duration, s	~0.25	~0.2	~0.35	~0.3
Peak luminosity, ergs s^{-1}	1.6×10^{45}	1.57×10^{45}	$\gtrsim 3.7 \times 10^{44}$	4.7×10^{44}
Energy release, ergs	1.3×10^{44}	1.04×10^{44}	$\gtrsim 6.8 \times 10^{43}$	5×10^{43}
Tail				
Exponential decay, s	~100	~100	~80	~80
Energy release, ergs	3×10^{44}	3.29×10^{44}	$\gtrsim 5.2 \times 10^{43}$	1.2×10^{44}
Total energy release in radiation, ergs	4.3×10^{44}	4.33×10^{44}	$\gtrsim 1.2 \times 10^{44}$	1.7×10^{44}
Energy release in neutrinos, ergs		1.4×10^{43}		2.5×10^{42}

radiation, some part of the energy Q may be emitted from the quark surface and observed as a giant burst.

In our case the thickness of the surface layer which is heated by accretion is very small compared with the stellar radius $R \simeq 10^6$ cm (see below), and a plane-parallel approximation may be used. We start with the equation of heat transfer that describes the temperature distribution at the surface layers of a strange star [15]:

$$C_q \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K_c \frac{\partial T}{\partial x}\right) - \varepsilon_\nu , \quad (1)$$

where

$$C_q \simeq 2.5 \times 10^{20} (n_b/n_0)^{2/3} T_9 \text{ ergs cm}^{-3}\text{ K}^{-1} \quad (2)$$

is the specific heat for SQM per unit volume,

$$K_c \simeq 6 \times 10^{20} \alpha_c^{-1} (n_b/n_0)^{2/3} \text{ ergs cm}^{-1}\text{ s}^{-1}\text{ K}^{-1} \quad (3)$$

is the thermal conductivity,

$$\varepsilon_\nu \simeq 2.2 \times 10^{26} \alpha_c Y_e^{1/3} (n_b/n_0) T_9^6 \text{ ergs cm}^{-3}\text{ s}^{-1} \quad (4)$$

is the neutrino emissivity, $n_0 \simeq 1.7 \times 10^{38}$ cm^{-3} is normal nuclear matter density, n_b is the baryon number density of SQM, $\alpha_c = g^2/4\pi$ is the QCD fine structure constant, g is the quark-gluon coupling constant, $Y_e = n_e/n_b$ is the number of electrons per baryon, and T_9 is the temperature in units of 10^9 K.

The heat flux due to thermal conductivity is

$$q = -K_c dT/dx . \quad (5)$$

At the stellar surface, the heat flux is directed into the strange star and coincides with the energy flux of the accreted matter at $0 \le t < \Delta t$, while at $t \ge \Delta t$ this flux is directed outside and coincides with the energy flux in e^+e^- pairs emitted from the SQM surface:

$$q \simeq \begin{cases} Q/(4\pi R^2 \Delta t) & \text{at } 0 \le t < \Delta t , \\ -\varepsilon_\pm f_\pm & \text{at } t \ge \Delta t , \end{cases} \quad (6)$$

where $\varepsilon_\pm \simeq m_e c^2 + kT_S$ is the mean energy of created e^+e^- pairs,

$$f_\pm \simeq 10^{39.2} \left(\frac{T_S}{10^9 \text{ K}}\right)^3 \exp\left(-\frac{11.9 \times 10^9 \text{ K}}{T_S}\right) J(\zeta) \text{ s}^{-1} \quad (7)$$

is the flux of pairs from the unit SQM surface,

$$J(\zeta) = \frac{1}{3} \frac{\zeta^3 \ln(1 + 2\zeta^{-1})}{(1 + 0.074\zeta)^3} + \frac{\pi^5}{6} \frac{\zeta^4}{(13.9 + \zeta)^4} , \quad (8)$$

and $\zeta \simeq (2 \times 10^{10} \text{ K})/T_S$ [14].

Equations (5)–(8) give a boundary condition on dT/dx at the stellar surface. We assume that at the initial moment, $t = 0$, the temperature in the surface layers is constant, $T = 3 \times 10^7$ K. In our model there are two parameters, Q and Δt, which describe the comet matter accretion onto the strange star.

III. *The light curves.*—The set of Eqs. (1)–(8) was solved numerically. We assumed the typical values of $\alpha_c = 0.1$, $n_b = 2n_0$, and $Y_e = 10^{-4}$. For $Q = 9.2 \times 10^{44}$ ergs and $\Delta t = 370$ s, Figs. 1 and 2 show the luminosity, $L_\pm = 4\pi R^2 \varepsilon_\pm f_\pm$, of the strange star in e^+e^- pairs as a function of time t at $t \ge \Delta t$. This luminosity is many orders of magnitude higher than

$$L_\pm^{\max} \simeq 4\pi m_e c^3 R/\sigma_{\rm T} \simeq 10^{36} \text{ ergs s}^{-1}, \quad (9)$$

where $\sigma_{\rm T}$ is the Thomson cross section. In this case, e^+e^- pairs outflowing from the stellar surface mostly annihilate in the vicinity of the strange star, $r \sim R$, and far from the star, $r \gg R$, the luminosity in pairs cannot be significantly

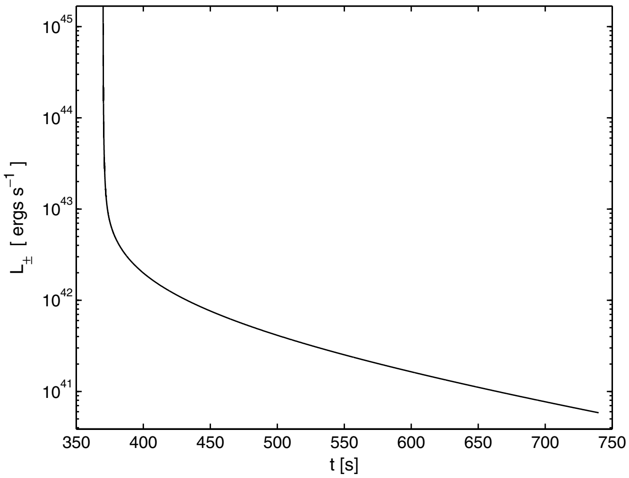

FIG. 1. The light curve expected in our model for $Q = 9.2 \times 10^{44}$ ergs and $\Delta t = 370$ s.

more than $L_\pm^{\max}$ [16]. Therefore, at $r \gg R$ the luminosity in x-ray and γ-ray photons practically coincides with the calculated value of $L_\pm$, $L_\gamma \simeq L_\pm - L_\pm^{\max} \simeq L_\pm$.

The light curve predicted in our model for $Q = 9.2 \times 10^{44}$ ergs and $\Delta t = 370$ s (see Figs. 1 and 2) is in good agreement with the light curve observed for the 5 March 1979 event (see Table I). This is the first earnest evidence that SGRs are strange stars, not neutron stars as usually assumed. It is worth noting that the theoretical light curve shown by Figs. 1 and 2 is averaged over 10 ms that is the highest time resolution of the observations made by the Pioneer Venus Orbiter [8]. From Table I we can see that the light curve of the 27 August 1998 event may be fitted fairly well in our model for $Q = 5.4 \times 10^{44}$ ergs and $\Delta t = 280$ s.

The surface layers heated by the accretion radiate in low-energy ($\lesssim 1$ MeV) neutrinos about 1% of the total thermal energy Q (see Table I). The neutrino light curve expected in our model for the 5 March 1979 event is shown by Fig. 3.

IV. *Discussion.*—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 [17]. In this particular model, there appear two typical masses ($\sim 10^{25}$ g and $\sim 10^{22}$ g) available for prompt infall. Accretion of cometlike objects with the first typical mass ($\Delta M \sim 10^{25}$ g) may result in the giant flares of SGRs as discussed above. The accretion time depends on ΔM and the impact parameter s. For $\Delta M \sim 10^{25}$ g and s less than the tidal breakup radius r_t ($\sim 10^{11}$ cm), this time is somewhere between $\sim l_c/v(l_c) \sim 0.1$ s and $\sim r_t/v(r_t) \sim 10^3$ s if the kinematic viscosity is high enough, where $l_c \sim 10^8$ cm is the comet radius, and $v(r) \simeq (GM/r)^{1/2}$ is the velocity at the distance r from the strange star of mass M [17]. The accretion time of ~ 300 s (see Table I) is in the allowed range and seems reasonable, especially if we take into account that the long time [$\sim r_t/v(r_t) \sim 10^3$ s] accretion of comets with $s \sim r_t$ is the most probable.

Figure 4 shows 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. This distribution 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 ($\lesssim 10^{-3}$ s) to the temperature shown by Fig. 4 by any other mechanism, for example, by decay of superstrong ($\sim 10^{14}$–10^{15} G) magnetic fields [18], the light curve of the subsequent radiation coincides with the light curve calculated above and shown by Figs. 1 and 2. The energy released by the magnetic field decay may be communicated to the surface by stellar pulsations, rather than any other mechanism [19]. The sound-wave crossing time through the strange star is $\sim 10^{-4}$ s, which is less than the upper

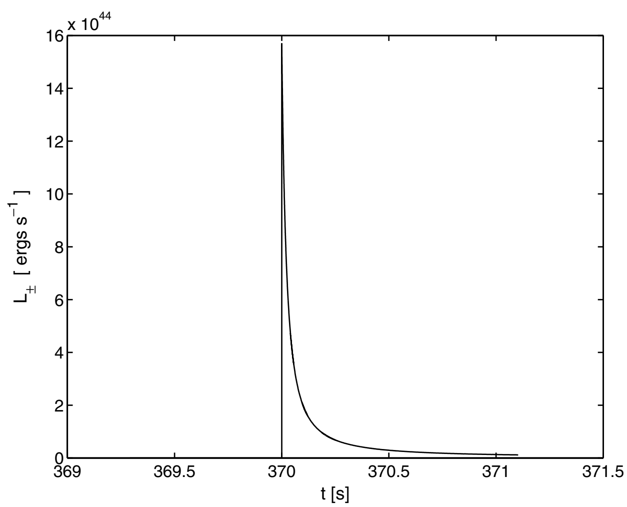

FIG. 2. The initial pulse of the light curve shown in Fig. 1.

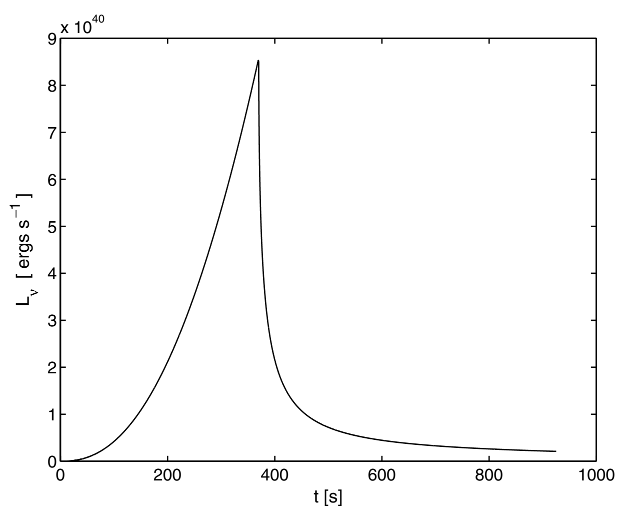

FIG. 3. The luminosity in neutrinos as a function of time for $Q = 9.2 \times 10^{44}$ ergs and $\Delta t = 370$ s.

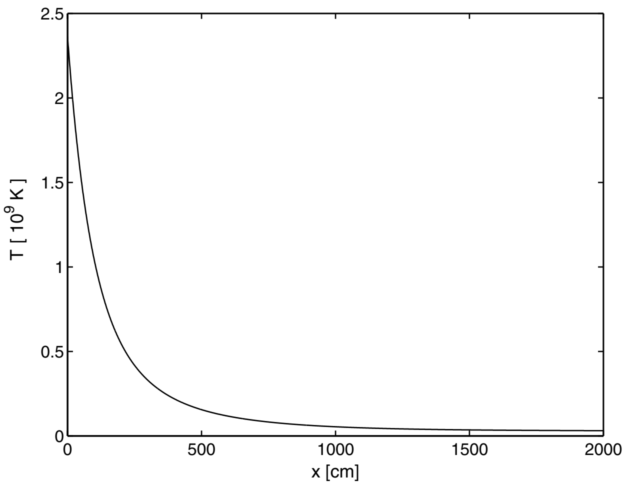

FIG. 4. The distribution of temperature in the surface layers at the moment $t = \Delta t = 370$ s.

limits in the rise time of the two giant bursts. The superstrong magnetic field can confine the radiating e^+e^- plasma [19]. This may be tested by observations of giant bursts [20], and the existence of superstrong magnetic fields may be verified.

In our model for SGRs, e^+e^- pairs are the main component of the thermal emission from the stellar surface [13,14]. In $\sim 10^4$ s after a giant burst, when the surface luminosity in pairs is $\sim L_{\pm}^{\max} \sim 10^{36}$ ergs s^{-1}, the annihilation radiation with the luminosity of $\sim L_{\pm}^{\max}$ escapes from the stellar vicinity more or less freely, and its spectrum is a very wide ($\Delta E/E \simeq 0.3$) line of energy $E \simeq 0.5$ MeV. Observations of such a line with the γ-ray spectrometer SPI in the forthcoming INTEGRAL mission can clarify the nature of SGRs.

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