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 comet-like object.

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 [4] that strange quark matter (SQM) composed of roughly equal numbers of up, down, and strange quarks plus a smaller 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 quarkonization [5]. It was shown that, with the uncertainties inherent in a nuclear-physics calculation, the existence of stable SQM has been studied in many papers (e.g., Ref. [2]), and it was observed that, with the quark matter (SQM) composed of roughly equal numbers of up, down, and strange quarks plus a smaller 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 quarkonization [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 lay-
ers 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 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 \( R \simeq 10^8 \) 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 \([15]\):

\[
C_q \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( K_c \frac{\partial T}{\partial x} \right) - \varepsilon_\nu, 
\]

where

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

is the specific heat for SQM per unit volume,

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

is the thermal conductivity,

\[
\varepsilon_\nu \simeq 2.2 \times 10^{36} \alpha_c Y_e^{1/3} (n_b/n_0) T_9^4 \text{ ergs cm}^{-3} \text{ s}^{-1} \tag{4}
\]

is the neutrino emissivity, \( n_0 \simeq 1.7 \times 10^{38} \text{ cm}^{-3} \) 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

\[
q = -K_c \frac{dT}{dx}. \tag{5}
\]

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

\[
\begin{align*}
q &\simeq \begin{cases} 
Q/(4\pi R^2 \Delta t) & \text{at } 0 \leq t < \Delta t, \\
-\varepsilon_\pm f_\pm & \text{at } t \geq \Delta t,
\end{cases} \\
\end{align*} \tag{6}
\]

where \( \varepsilon_\pm \approx m_e c^2 + kT_s \) is the mean energy of created \( e^+e^- \) pairs,

\[
f_\pm \approx 10^{39.2} T_{9,9}^3 \exp \left( -\frac{11.9}{T_{9,9}} \right) J(\zeta) \text{ cm}^{-2} \text{ s}^{-1} \tag{7}
\]

is the flux of pairs from the unit SQM surface,

\[
J(\zeta) = \frac{1}{3} \left( 1 + 2\zeta^{-1} \right) + \frac{\pi^5}{6} \left( 13.9 + \zeta^4 \right), \tag{8}
\]

and \( \zeta \approx (2 \times 10^{10} \text{ K})/T_s [14] \).

Eqs. (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, \( T = 3 \times 10^7 \text{ K} \). In our model there are two parameters, \( Q \) and \( \Delta t \), 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 \( Q = 9.2 \times 10^{44} \text{ ergs and } \Delta t = 370 \text{ s} \), Figures 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 \( t \geq \Delta t \). This luminosity is many orders of magnitude higher than

\[
L_{\pm}^\text{max} \simeq 4\pi m_e c^3 R/\sigma_T \simeq 10^{36} \text{ ergs s}^{-1}, \tag{9}
\]

where \( \sigma_T \) 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 more than \( L_\pm^\text{max} [16] \). Therefore, at \( r \gg R \) the luminosity in X-ray and \( \gamma \)-ray photons practically coincides with the calculated value of \( L_\pm \).

The light curve predicted in our model for \( Q = 9.2 \times 10^{44} \text{ ergs and } \Delta t = 370 \text{ s} \) (see Figs. 1 and 2) is in good agreement with the light curve observed for the 5 March 1979 event (see Table 1). 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 Figures 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 1 we can see that the light curve of the 27 August 1998 event may be fitted fairly well in our model for \( Q = 5.4 \times 10^{44} \text{ ergs and } \Delta t = 280 \text{ s} \).

The surface layers heated by the accretion radiate in low-energy (\( \lesssim 1 \) MeV) neutrinos about one per cent of the total thermal energy \( Q \) (see Table 1). The neutrino light curve expected in our model for the 5 March 1979 event is shown by Figure 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 [18]. 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 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 \( \Delta M \) 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 \( t_0/v(r_c) \sim 0.1 \) 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 \( M [18] \). The
accretion time of $\sim 300$ s (see Table 1) is in the allowed range and seems reasonable.

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 Figure 4 by any other mechanism, for example by decay of superstrong ($\sim 10^{14} - 10^{15}$ G) magnetic fields \cite{17}, the light curve of the subsequent radiation coincides with the light curve calculated above and shown by Figures 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 \cite{13}. The sound-wave crossing time through the strange star is $\sim 10^{-4}$ s, which is less than the upper limits in the rise time of the two giant bursts. The superstrong magnetic field can confine the radiating $e^+e^-$ plasma \cite{20}. This may be tested by observations of giant bursts \cite{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 \cite{13,17}. In $\sim 10^4$ s after a giant burst, when the surface luminosity in pairs is $\sim L^\text{max}_e \sim 10^{36}$ ergs s$^{-1}$, the annihilation radiation with the luminosity of $\sim L^\text{max}_e$ 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 $\gamma$-ray spectrometer SPI in the forthcoming INTEGRAL mission can clarify the nature of SGRs.

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

|                         | SGR 0526$-$66 | SGR 1900$+$14 |
|-------------------------|---------------|---------------|
| **Distance**            | 50 kpc        | 10 kpc        |
|                         | observations  | theory        |
| **Giant outburst**      | March 5, 1979 | August 27, 1998 |
| **Accretion of matter**|               |               |
| Duration $\Delta t$, s  | 370           | 280           |
| Energy release $Q$, ergs| $9.2 \times 10^{44}$ | $5.4 \times 10^{44}$ |
| **Initial pulse**       |               |               |
| Duration, s             | $\sim 0.25$   | $\sim 0.2$    |
| Peak luminosity, ergs s$^{-1}$ | $1.6 \times 10^{45}$ | $1.4 \times 10^{45}$ |
| Energy release, ergs    | $1.3 \times 10^{44}$ | $10^{44}$ |
|                         | $\gtrsim 6.8 \times 10^{43}$ | $4 \times 10^{44}$ |
| **Tail**                |               |               |
| Exponential decay, s    | $\sim 100$    | $\sim 100$   |
| Energy release, ergs    | $3 \times 10^{44}$ | $3.3 \times 10^{44}$ |
|                         | $\gtrsim 5.2 \times 10^{43}$ | $1.2 \times 10^{44}$ |
| **Total energy release**|               |               |
| in radiation, ergs      | $4.3 \times 10^{44}$ | $4.3 \times 10^{44}$ |
|                         | $\gtrsim 1.2 \times 10^{44}$ | $1.7 \times 10^{44}$ |
| **Energy release**      |               |               |
| in neutrinos, ergs      | $1.4 \times 10^{43}$ | $2.5 \times 10^{42}$ |
Figure captions

Fig. 1. The light curve expected in our model for $Q = 9.2 \times 10^{44}$ ergs and $\Delta t = 370$ s.
Fig. 2. The initial pulse of the light curve shown in Figure 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.
$L_\mp$ [ergs s$^{-1}$]

$t$ [s]
$L^\pm \ [\text{ergs s}^{-1}]$

$t \ [\text{s}]$
