THERMAL EMISSION FROM BARE QUARK MATTER SURFACES OF HOT STRANGE STARS

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Received 2000 December 5; accepted 2001 February 26; published 2001 March 21

ABSTRACT

We consider the thermal emission of photons and $\nu\nu^-$ pairs from the bare quark surface of a hot strange star. The radiation of high-energy ($\approx 20$ MeV) equilibrium photons prevails at the surface temperature $T_s \gtrsim 5 \times 10^{10}$ K, while below this temperature, $8 \times 10^8$ K $< T_s < 5 \times 10^{10}$ K, emission of $\nu\nu^-$ pairs created by the Coulomb barrier at the quark surface dominates. The thermal luminosity of a hot strange star in both photons and $\nu\nu^-$ pairs is estimated.

Subject headings: radiation mechanisms: thermal — stars: neutron

1. INTRODUCTION

Witten (1984) pointed out that strange quark matter (SQM) composed of roughly equal numbers of up, down, and strange quarks may be the absolute ground state of the strong interaction, i.e., absolutely stable with respect to $^{56}$Fe. Detailed studies showed that, with the uncertainties inherent in a nuclear physics calculation, the existence of stable SQM is reasonable (e.g., Farhi & Jaffe 1984; Chmaj & Slominski 1989; Terazawa 1990; Kettner et al. 1995; Weber 1999). If Witten’s idea is true, at least some of the compact objects known to astronomers as pulsars, powerful, accreting X-ray sources, X-ray and $\gamma$-ray bursters, etc., might be strange stars, not neutron stars as usually assumed (Alcock, Farhi, & Olinto 1986; Glendenning 1990, 1996; Caldwell & Friedman 1991; Madsen & Olesen 1991; Cheng & Dai 1996; 1998; Xu, Qiao, & Zhang 1999). SQM with a density of $\sim 10^{14}$ g cm$^{-3}$ can exist, by hypothesis, up to the surface of strange stars. This differs qualitatively from the case of a neutron star surface and opens observational possibilities to distinguish strange stars from neutron stars, if indeed the former exist. In this Letter, we consider thermal emission of photons and $\nu\nu^-$ pairs from the bare SQM surfaces of hot strange stars.

2. BARE QUARK SURFACES OF STRANGE STARS

AND THERMAL EMISSION

At the bare SQM surface of a strange star the density changes abruptly from $\sim 5 \times 10^{14}$ 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. The SQM surface is a very poor radiator of thermal photons at energies less than about 20 MeV (Alcock et al. 1986). This is because the plasma frequency that is related to the particle density of quarks is very high (see below).

2.1. Thermal Equilibrium Radiation

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 (e.g., Adams, Ruderman, & Woo 1963; Alcock et al. 1986):

$$\omega^2 = \omega_p^2 + k^2 c^2, \quad (1)$$

where $\omega$ is the frequency of electromagnetic waves, $k$ is their wavenumber,

$$\omega_p = \left( \frac{8 \pi e^2 c^2 n_b}{3 \mu} \right)^{1/2} \quad (2)$$

is the plasma frequency, $n_b$ is the baryon number density of SQM, and $\mu \approx \hbar c (\pi^2 n_b)^{1/3}$ is the chemical potential of quarks. Equation (1) is the familiar dispersion relation for a plasma, propagating modes exist only for $\omega > \omega_p$. Taking this into account, equation (2) yields the lower limit on the energy of electromagnetic quanta that are in thermodynamic equilibrium with quarks, $\epsilon_p = \hbar \omega > \hbar \omega_p \approx 18.5 (n_b/n_0)^{1/3}$ MeV, where $n_0 = 0.17$ fm$^{-3}$ is normal nuclear matter density. At the SQM surface where the pressure is zero, we expect $n_0 = (1.5-2) n_b$ and $\hbar \omega_p \approx 20-25$ MeV (e.g., Farhi & Jaffe 1984; Alcock et al. 1986; Chmaj, Haensel, & Slominski 1991). Therefore, the spectrum of thermal equilibrium photons radiated from the bare SQM surfaces of strange stars is expected to be very hard.

The energy flux emitted from the unit surface of SQM in thermal equilibrium photons is (Bekoff 1966; Chmaj et al. 1991)

$$F_{\nu\nu} = \frac{\hbar}{c^2} \int_0^\infty d\omega \frac{\omega^2 - \omega_p^2}{\exp (\hbar \omega/k_B T_s)} - 1 , \quad (3)$$

where

$$g(\omega) = \frac{1}{2 \pi^2} \int_0^{\pi/2} d\vartheta \sin \vartheta \cos \vartheta D(\omega, \vartheta), \quad (4)$$

$k_B$ is the Boltzmann constant, $D(\omega, \vartheta)$ is the coefficient of radiation transmission from SQM to vacuum, $D = 1 - (R_1 + R_2)/2$, and

$$R_1 = \frac{\sin^2 (\vartheta - \vartheta_0)}{\sin^2 (\vartheta + \vartheta_0)}, \quad R_2 = \frac{\tan^2 (\vartheta - \vartheta_0)}{\tan^2 (\vartheta + \vartheta_0),} \quad (5)$$

$$\vartheta_0 = \arcsin \left[ \sin \vartheta \sqrt{1 - (\omega_p^2/\omega^2)} \right] \quad (6)$$

(see, e.g., Landau, Lifshitz, & Pitaevskii 1984). Figure 1 shows the ratio of the equilibrium photon emissivity of the bare surface of hot SQM to the blackbody surface emissivity, $\xi_{\nu\nu} = F_{\nu\nu}/F_{BB}$, where $F_{BB} = \sigma T_s^4$ and $\sigma$ is the Stefan-Boltzmann con-
the electrons from escaping to infinity, counterbalancing the de-

When the electric field is generated in the surface layer to prevent

et al. 1986). This field is a few ten times higher than the critical

\textit{extremely high, the empty states below the pair creation threshold,}

\textit{production below the pair creation threshold. The thermal energy of}

\textit{of energy for the process of pair creation.}

\textit{The flux of $e^+e^-$ pairs from the unit surface of SQM is (Usov 1998)}

\begin{equation}
\dot{n}_e = \Delta r_e \Delta n_e \tau_{th}^{-1},
\end{equation}

\begin{equation}
\Delta n_e = \frac{3 k_B T_e}{\varepsilon_F} \exp \left( - \frac{2m^2 c^2}{k_B T_e} \right) n_e
\end{equation}

\textit{is the density of electronic empty states with energies below}

\textit{the pair creation threshold at thermodynamical equilibrium, and}

\textit{is the characteristic time of thermalization of electrons.}

\textit{In the surface electron layer, the spectrum of electrons is}

\textit{eralized because of electron-electron collisions, and the}

\textit{eralization time is about $\varepsilon_F^{-1}$ where (e.g., Potekhin et al. 1999)}

\begin{equation}
\nu_e = \frac{3}{2\pi} \left( \frac{\alpha}{\pi} \right)^{1/2} \frac{(k_B T_e)^2}{\hbar \varepsilon_F} J(\xi)
\end{equation}

\textit{is the frequency of electron-electron collisions for degener-

\textit{ate electrons with} $\varepsilon_F \gg m^2 c^2$, $\alpha = e^2/\hbar c = 1/137$ is the fine-

\textit{structure constant (cf. Usov 1998)},

\begin{equation}
J(\xi) = \frac{1}{3} \xi^3 \ln \left( 1 + \frac{2}{\xi^2} \right) + \frac{\pi^3}{6} \frac{\xi^4}{(13.9 + \xi)^4},
\end{equation}

\textit{For typical parameters,} $\Delta T_e = 500$ \textit{fm and} $\varepsilon_F = 18$ \textit{MeV,}

\textit{equations (7), (8), and (9) yield}

\begin{equation}
\dot{n}_e \approx 10^{10} \left( \frac{T_s}{10^9 \text{K}} \right)^3 \exp \left[ -11.9 \left( \frac{T_s}{10^9 \text{K}} \right)^{-1} \right] J(\xi) \text{ s}^{-1}
\end{equation}

\textit{within a factor of 2 or so.}

\textit{The energy flux from the unit surface of SQM in $e^+e^-$ pairs}

\textit{created by the Coulomb barrier is} $F_s = \varepsilon_F \dot{n}_s$, \textit{where}

\textit{the mean energy of created particles and}

\textit{is given by equation (12). Figure 1 shows the ratio of}

\textit{the SQM surface emissivity in $e^+e^-$ pairs to the blackbody surface}

\textit{emissivity,} $\xi_s/T_e^{3/2} = \xi_{\text{BB}}$, \textit{versus the surface temperature} $T_e$.

\textit{Creation of $e^+e^-$ pairs by the Coulomb barrier is the main}

\textit{mechanism of thermal emission from the surface of SQM at}

\textit{$8 \times 10^8$ K} \textit{$T_e \approx 5 \times 10^9$ K, while the equilibrium radiation}

\textit{dominates at extremely high temperatures,} $T_e > 5 \times 10^9$ \textit{K.}

\textit{The SQM surface emissivity in photons at energies} $\varepsilon_\gamma < \hbar\omega_s$ \textit{is strongly suppressed (see above). However, low-energy}

\textit{photons may leave SQM if they are produced by a nonequili-

\textit{brium process in the surface layer with the thickness of}

\textit{cm. The emissivity of SQM in nonequilibrium}

\textit{quark-quark bremsstrahlung radiation at low energies,} $\varepsilon_\gamma <
\[ \hbar \omega_{ee'} \text{ has been estimated by Chmaj et al. (1991), } \xi_{neq} = F_{neq}/F_{BB} \approx 10^{-4}. \text{ Chmaj et al. (1991) made a few assumptions that led to an overestimate of } \xi_{neq} \text{ and } \xi_{neq} \approx 10^{-4} \text{ is, in fact, an upper limit. Hence, our estimate of the SQM surface emissivity, } \xi = \xi_{neq} + \xi_s \text{, is valid for } T_S \gtrsim 8 \times 10^8 \text{ K when } \xi_s \text{ is more than } \sim 10^{-3} \text{ (see Fig. 1). For } T_S < 8 \times 10^8 \text{ K, the value of } \xi \text{ is uncertain, } \xi_s \ll \xi \ll 10^{-2}, \text{ especially at low energies of photons.} \]

2.3. Thermal Radiation from a Hot Strange Star

At \( T_S \gtrsim 8 \times 10^8 \text{ K} \) the total luminosity of a bare strange star in both photons and \( e^+e^- \) pairs is

\[ L = L_{neq} + L_{ee} = 4\pi R^2 (F_{neq} + F_{ee}), \quad (13) \]

where \( R \approx 10^6 \text{ cm} \) is the radius of the strange star. Figure 2 shows the value of \( L \) as a function of the surface temperature \( T_S \). At \( T_S < 8 \times 10^8 \text{ K} \) the total luminosity is somewhere between \( \sim 4\pi R^2 F_{ee} \) and \( \sim 10^{-3} R^2 F_{BB} \).

At \( T_S \approx 8 \times 10^8 \text{ K} \) the luminosity in \( e^+e^- \) pairs created by the Coulomb barrier at the SQM surface is very high, \( L_{ee} \approx 10^{40} \text{ ergs s}^{-1} \) (see Fig. 2), that is, at least 4 orders of magnitude higher than

\[ L_{ee} \approx 4\pi R^2 c^3 \sigma_T \approx 10^{36} \text{ ergs s}^{-1}, \quad (14) \]

where \( \sigma_T \) is the Thomson cross section. In this case, the timescale \( t_{ann} \sim (n_e \sigma_T) \) for annihilation of \( e^+e^- \) pairs is much shorter than the timescale \( t_{esc} \sim R/c \) for their escape, \( t_{ann}/t_{esc} = L_{ee}/L_{neq} < 10^4 \ll 1 \), and \( e^+e^- \) pairs outflowing from the stellar surface mostly annihilate in the vicinity of the strange star, \( r \sim R \) (Beloborodov 1999 and references therein). The total luminosity is not very high, \( L \approx 10^{32} \text{ ergs s}^{-1} \), the luminosity in \( e^+e^- \) pairs at the distance \( r \gg R \) cannot be essentially more than \( L_{ee} \). At \( L \gg 10^{32} \text{ ergs s}^{-1} \), the outflowing \( e^+e^- \) wind is relativistic, and the luminosity in pairs at \( r \gg R \) is \( \sim L_{ee}^{ann} (L/10^{32} \text{ ergs s}^{-1})^{1/3} < 10^4 L \text{ (e.g., Usov 1994; Lyutikov \\& Usov 2000). Hence, far from a bare strange star with surface temperature \( T_S \approx 8 \times 10^8 \text{ K} \) the photon luminosity dominates irrespective of \( T_S \) and practically coincides with the total luminosity given by equation (13).}

3. DISCUSSION

In this Letter, we have considered the thermal emission from the bare SQM surface of a hot strange star. The SQM surface emissivity in both photons and \( e^+e^- \) pairs is estimated for \( T_S \gtrsim 8 \times 10^8 \text{ K} \). We found that at \( T_S \gtrsim 1.5 \times 10^9 \text{ K} \) the SQM surface emissivity is \( \approx 10\% \) of the blackbody surface emissivity. Below this temperature, \( T_S \lesssim 1.5 \times 10^9 \text{ K} \), the SQM surface emissivity decreases rapidly with decrease of \( T_S \), and at \( T_S < 8 \times 10^8 \text{ K} \) it is at least 4 orders of magnitude smaller than the emissivity of the blackbody surface.

Recenty, it was argued that SQM is a superconductor if its temperature is not too high (for a review, see Rajagopal \\& Wilczek 2000). In this case, the nonequilibrium quark-quark bremsstrahlung radiation discussed in Chmaj et al. (1991) is completely suppressed, and equation (13) may be used at \( T_S \lesssim 8 \times 10^8 \text{ K} \) as well.

"Normal" matter (ions and electrons) may be present at the SQM surface of a strange star. The ions in the inner layer are supported against the gravitational attraction to the underlying strange star by the very strong electric field of the Coulomb barrier. There is an upper limit to the amount of normal matter at the quark surface, \( \Delta M \approx 10^{-3} M\odot \) (Glendenning \\& Weber 1992). Such a massive envelope of normal matter with \( \Delta M \approx 10^{-3} M\odot \) completely obscures the quark surface. However, it was pointed out (e.g., Haensel, Paczynski, \\& Amstersdami 1991) that a strange star at the moment of its formation is very hot. The temperature in the stellar interior may be as high as a few times \( 10^{11} \text{ K} \). The rate of mass ejection from such a hot compact star is very high (e.g., Woosley \\& Baron 1992; Levinson \\& Eichler 1993; Woosley 1993), and, most probably, the normal-matter envelope is blown away by radiation pressure. High temperatures also lead to considerable reduction of the Coulomb barrier, increasing the tunneling of nuclei through the barrier toward the SQM surface (Kettner et al. 1995). Therefore, it is natural to expect the SQM surface of a very young strange star to be nearly (or completely) bare. It was argued that the normal-matter atmosphere of such a star remains optically thin until the temperature of the SQM surface is higher than \( \sim 3 \times 10^7 \text{ K} \) (Usov 1997).

Since SQM at the surface of a bare strange star is bound via strong interaction rather than gravity, such a star can radiate at a luminosity greatly exceeding the Eddington limit at the stellar mass of \( \sim M_{\odot} \) (Alcock et al. 1986; Chmaj et al. 1991; Usov 1998 and this Letter). Therefore, bare strange stars are reasonable candidates for soft \( \gamma \)-ray repeaters (SGRs) that are the sources of short bursts of high-frequency (X-ray and \( \gamma \)-ray) emission with super-Eddington luminosities, up to \( \sim 10^{43} - 10^{45} \text{ ergs s}^{-1} \). The bursting activity of SGRs may be explained by fast heating of the stellar surface up to the temperature of \( \sim (1-2) \times 10^9 \text{ K} \) (see Fig. 2) and its subsequent thermal emission. The heating mechanism may be either impacts of comets onto bare strange stars (Zhang, Xu, \\& Qiao 2000) or fast decay of superstrong \( \sim 10^{13}-10^{14} \text{ G} \) magnetic fields (Usov 1984; Thompson \\& Duncan 1995; Heyl \\& Kulkarni 1998).

This work was supported by the Israel Science Foundation of the Israel Academy of Sciences and Humanities.
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