Radiation from hot bare strange stars

A.G. Aksenov,1,2 M. Milgrom,1 and V.V. Usov,1
1Department of Condensed Matter Physics, Weizmann Institute, Rehovot 76100, Israel
2Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya, 25, Moscow 117259, Russia

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ABSTRACT
We present the results of numerical simulations of stationary, spherically outflowing, $e^\pm$ pair winds, with total luminosities of $L = 10^{35} - 10^{42}$ ergs s$^{-1}$. These results have direct relevance to the emission from hot, bare, strange stars, which are thought to be powerful sources of pairs created by the Coulomb barrier at the quark surface. The spectra of emergent photons and pairs are calculated. For $L > 2 \times 10^{35}$ ergs s$^{-1}$, photons dominate the emerging emission. As $L$ increases from $\sim 10^{35}$ to $10^{42}$ ergs s$^{-1}$, the mean photon energy decreases from $\sim 400 - 500$ keV to 40 keV, while the spectrum changes in shape from a wide annihilation line to being nearly blackbody with a high energy ($> 100$ keV) tail. Such a correlation of the photon spectrum with the luminosity, together with the fact that super-Eddington luminosities can be achieved, might be a good observational signature of hot, bare, strange stars.

Key words: radiation mechanisms: thermal — plasmas — X-rays: stars — radiative transfer — stars: neutron

1 INTRODUCTION
Strange stars made entirely of deconfined quarks have long been proposed as a possible alternative to neutron stars (e.g., Witten 1984; Alcock, Farhi, & Olinto 1986a; Haensel, Zdunik, & Schaeffer 1986). Because strange quark matter (SQM) at the surface of a bare strange star is bound by strong interactions, not by gravity, such a star can radiate with luminosities greatly exceeding the Eddington limit. Luminosities as high as $10^{52}$ ergs s$^{-1}$ can be radiated briefly after the formation of the star, when the surface temperature is $T_s \sim 10^{13}$ K (Alcock et al. 1986a; Chmaj, Haensel, & Slonimski 1991; Usov 1998, 2001a). Some 10 seconds after formation, $T_s$ drops to less than $10^{10}$ K (Page & Usov 2002). At such temperatures—which may also prevail later in the life of the star due to episodes of reheating—electron–positron ($e^\pm$) pairs created by the Coulomb barrier at the surface take up most of the thermal emission from the SQM surface (Usov 2001a). Some of these pairs annihilate into photons, thus forming a pair-photon wind that flows away from the star.

For the typical radius of a strange star ($10^6$ cm), a temperature of $T_s \sim 10^9 - 10^{10}$ K gives an energy injection rate in pairs $\dot{E} \sim 10^{43} - 10^{49}$ ergs s$^{-1}$ (Usov 2001a). For such powerful winds the pair density near the surface is very high, and the outflowing pairs and photons are very nearly in thermal equilibrium almost up to the wind photosphere (e.g., Paczynski 1990). The outflow may then be described fairly well by relativistic hydrodynamics (Paczynski 1986, 1990; Goodman 1986; Grimsrud & Wasserman 1998; Iwamoto & Takahara 2002). The emerging emission consists mostly of photons, so $L_\gamma \simeq \dot{E}$. The photon spectrum is roughly a black body with a temperature of $\sim 10^{15}(\dot{E}/10^{48}$ ergs s$^{-1})^{1/4}$ K. The emerging luminosity in $e^\pm$ pairs is very small, $L_e = \dot{E} - L_\gamma \sim 10^{-6}L_\gamma \ll L_\gamma$. All this applies roughly down to $\dot{E} \sim 10^{42} - 10^{43}$ ergs s$^{-1}$.

In contradistinction, for $\dot{E} < 10^{42}$ ergs s$^{-1}$ ($T_s < 9 \times 10^8$ K), which is the region we explore, the thermalization time for the pairs and photons is longer than the escape time, and pairs and photons are not in thermal equilibrium. In this Letter, we describe (for the first time to our knowledge) the results of numerical calculations of the characteristics of the emerging emission in pairs and photons in stationary winds with energy injection rates $\dot{E} = 10^{35} - 10^{42}$ ergs s$^{-1}$. The details of the set-up, code, processes included, and the results for the wind structure, will be described elsewhere (Aksenov, Milgrom, & Usov 2003). Here we give a brief account.

2 FORMULATION OF THE PROBLEM
At the moment of formation of a strange star, the temperature in the stellar interior is expected to be a few times $10^{11}$ K (Haensel, Paczynski, & Amsterdamski 1991; Cheng & Dai 2001). The neutrino luminosity of such a hot strange star is up to $\sim 10^{34}$ ergs s$^{-1}$. The rate of neutrino-induced ejection of normal matter, which may be present at the SQM surface (Alcock et al. 1986a; Glendenning & Weber 1992), is very high (e.g., Woosley & Baron 1992; Levinson & Eichler...
follows that this may be the case for at least a few hundred years after formation, and perhaps a few orders longer, depending on the phase of SQM, convection, etc. (Page & Usov 2002)

We consider an $e^{\pm}$ pair wind that flows away from a hot, bare, unmagnetized, strange star with a radius of $R = 10^8$ cm. Pairs are injected from time $t = 0$ at a constant rate into the wind, which is assumed spherical. This results in a time-dependent wind which eventually becomes stationary.

We solve numerically the coupled, relativistic Boltzmann equations for the pairs (e.g., Mezzacappa & Bruenn 1993; Aksenov et al. 2003)

\[
\frac{1}{c} \frac{\partial E_i}{\partial t} + \frac{\mu}{r^2} \frac{\partial}{\partial r} (r^2 E_i) + \frac{1}{r} \frac{\partial}{\partial r} \left[ (1 - \mu^2) \beta_i E_i \right] = \sum_q [\eta^q_i - \chi^q_i E_i],
\]

where $E_i(\epsilon, \mu, r, t) = 2r \epsilon^3 \beta_i f_i(\epsilon^3)$ are the $\{r, \mu \}$-phase-space energy densities of $e^{\pm}$ pairs ($i = e$) and photons ($i = \gamma$) ($f_i$ being the distribution functions); $\mu = \cos \theta$, $-1 \leq \mu \leq 1$, where $\theta$ is the angle between the radius-vector $\mathbf{r}$ and the particle momentum $\mathbf{p}$; $\beta_e = 1$, $\beta_\gamma = \nu_e/c = \sqrt{1 - (m_e c^2/\epsilon^3)}$; $\epsilon$ is the particle energy; $\eta^q$ is the emission coefficient for the energy production by a particle of type $i$ via the physical process labelled by $q$; and, $\chi^q_i$ is the corresponding absorption coefficient. The summation runs over all considered physical processes. Gravity is neglected [but will be included in our more detailed calculations (Aksenov et al. 2003)]. This is a good approximation for the energy injection rates we explore, because $L \approx 10^{35}$ ergs s$^{-1}$ is the Eddington luminosity for the pair plasma, and above it, radiation-pressure forces dominate over gravity.

At the internal boundary, $r = R$, the input pair number flux depends on the temperature $T_S$ at the stellar surface alone, and is taken as (Usov 2001a)

\[
F_e = 10^{39} \left( \frac{T_S}{10^9 \text{K}} \right)^3 \exp \left[ -11.9 \left( \frac{T_S}{10^9 \text{K}} \right)^{-1} \right] \times \frac{\zeta}{3(1 + 0.074 c)} \left( \frac{\beta_e}{6(13.9 + \zeta)} \right) \epsilon^2 \text{cm}^{-2} \text{s}^{-1},
\]

where $\zeta = 20(T_S/10^9 \text{K})^{-1}$. Their energy spectrum is thermal with temperature $T_S$, and their angular distribution is isotropic for $0 \leq \mu \leq 1$. The energy injection rate in $e^{\pm}$ pairs is then

\[
\dot{E} = 4\pi R^2 [m_e c^2 + (3/2)k_B T_S] F_e,
\]

where $k_B$ is the Boltzmann constant.

The stellar surface is assumed to be a perfect mirror for both $e^{\pm}$ pairs and photons. At the external boundary ($r = r_{\text{ext}}$), the pairs and photons escape freely from the studied region.

The thermal emission of pairs used in our simulations [eq. (2)] is that expected in the normal, unpaired, phase of SQM. However, it has been argued that SQM is a color superconductor with a critical temperature of $\sim 10^{11} - 10^{12}$ K (for a review, see Alford, Bowers, & Rajagopal 2001; Rajagopal & Wilczek 2001). It is expected that at density much higher than the mean nuclear density, $\rho_n \approx (2 - 3) \times 10^{14}$ g cm$^{-3}$, the color superconductor is in the “Color-Flavor-Locked” (CFL) phase, in which quarks of all three flavors and three colors are paired in a single condensate. If the density is only slightly higher than $\rho_n$, SQM may be in the “2 color-flavor Superconductor” (2SC) phase in which only up and down quarks of two colors are paired while the ones of the third color and the strange quarks of all three colors are unpaired. In the CFL phase, SQM is electrically neutral and no electrons are present. So, if at the surface the SQM is in the CFL phase, there is no supercritical electric field and no $e^{\pm}$ pair emission. In the 2SC phase, electrons are present, and the thermal emission of $e^{\pm}$ pairs from the surface is practically the same as for normal SQM. Therefore, our simulations pertain only to the last two cases.

Although the injected pair plasma contains no radiation, as the plasma moves outwards, photons are produced by pair annihilation. Other two body processes that we include in our simulations are Møller ($e^+ e^- \rightarrow e^+ e^-$ and $e^- e^- \rightarrow e^+ e^-$) and Bhabha ($e^+ e^- \rightarrow e^+ e^-$) scattering, Compton scattering ($\gamma e \rightarrow \gamma e$), and photon-photon pair production ($\gamma \gamma \rightarrow e^+ e^-$). Two body processes do not change the total number of particles in a system and thus cannot, in themselves, lead to thermal equilibrium. For this reason, we include bremsstrahlung ($ee \rightarrow ee$), double Compton scattering ($\gamma e \rightarrow \gamma e$), and three quantum annihilation ($e^+ e^- \rightarrow \gamma \gamma \gamma$), which change the particle number, even though their cross-sections are $\sim \alpha^{-1} \sim 10^2$ times smaller than those of the two body processes ($\alpha$ is the fine-structure constant).

3 NUMERICAL RESULTS

We give here the results for the properties of the emerging radiation after stationarity is achieved, so the total wind luminosity is equal to the energy injections rate: $L = L_e + L_\gamma = \dot{E}$. We present results for different values of $L$, which is the only free parameter. The corresponding surface temperature
photons, we see that for $L < L_\text{sim}$ simply reflects the fact that for $L < L_\ast$, the pair-annihilation time is longer than the escape time, and the injected pairs remain mostly intact. At higher luminosities, most pairs annihilate before escape, and reconversion into pairs is inefficient, as the mean energy of photons at the photosphere is rather below the pair-creation threshold.

Figures 2 and 3 represent the energy spectra of the emerging photons and pairs for different values of $L$. At low luminosities, $L \sim 10^{35} - 10^{37}$ ergs s$^{-1}$, photons that form in annihilation of $e^\pm$ pairs escape from the vicinity of the strange star more or less freely, and the photon spectra resembles a very wide annihilation line. The small decrease in mean photon energy $\langle \epsilon_\gamma \rangle$ from $\sim 500$ keV at $L \sim 10^{35}$ ergs s$^{-1}$ to $\sim 400$ keV at $L \sim 10^{37}$ ergs s$^{-1}$ occurs because of the energy transfer from annihilation photons to $e^\pm$ pairs via Compton scattering (see Fig. 1). As a result of this transfer, the emerging $e^\pm$ pairs are heated up to the mean energy $\langle \epsilon_\gamma \rangle \sim 400$ keV at $L \sim 10^{37}$ ergs s$^{-1}$. For $L > 10^{37}$ ergs s$^{-1}$, changes in the particle number due to three body processes are essential, and their role in thermalization of the outflowing plasma increases with the increase of $L$. We see in Figure 2 that, for $L = 10^{34}$ ergs s$^{-1}$, the photon spectrum is near blackbody, except for the presence of a high-energy tail at $\epsilon_\gamma > 100$ keV. At this luminosity, the mean energy of the emerging photons is $\sim 40$ keV, while the mean energy of the blackbody photons is $\sim 30$ keV (see Fig. 4). (The energy resolution in our simulations is $\sim 20$ keV.)

For $L \sim 10^{42}$ ergs s$^{-1}$, the emerging pair energy spectrum is close to a Maxwellian, while for $L < 10^{40}$ ergs s$^{-1}$ it deviates significantly from it (see Fig. 3).

**4 DISCUSSION**

We have identified certain characteristics of the expected radiation from hot, bare, strange stars that we hope will help identify such stars, if they exist. The spectrum, we find, is rather hard for the studied luminosity range. This makes such stars amenable to detection and study by sensitive, high energy instruments, such as INTEGRAL (e.g., Schoenfelder 2001), which is more sensitive in this range than previous detectors.

As super-Eddington luminosities and, as we find, hard X-ray spectra characterize the emission from bare, strange stars, soft $\gamma$-ray repeaters (SGRs), which are the sources of short bursts of hard X-rays with super-Eddington luminosities (up to $\sim 10^{42} - 10^{45}$ ergs s$^{-1}$), are reasonable candidates for strange stars (e.g., Alcock, Farhi, & Olinto 1986b; Cheng...
& Dai 1998; Usov 2001b). The bursting activity of SGRs may be explained by fast heating of the stellar surface up to the temperature of \( \sim (1 - 2) \times 10^9 \) K and its subsequent thermal emission (Usov 2001b,c). The heating mechanism may be either impacts of comets onto bare strange stars (Zhang, Xu, & Qiao 2000; Usov 2001b) or fast decay of superstrong \( (\sim 10^{14} - 10^{15}) G \) magnetic fields (Usov 1984; Thompson & Duncan 1995; Heyl & Kulkarni 1998). For typical luminosities of SGRs \( (L \sim 10^{42} - 10^{43} \text{ ergs s}^{-1}) \), the mean photons energy we find is \( \sim 40 \text{ keV} \) (see Fig. 4), which is consistent with observations of SGRs (Hurley 2000).

Another important idiosyncrasy that we find is a strong anti-correlation between spectral hardness and luminosity. While at very high luminosities \( (L > 10^{42} - 10^{43} \text{ ergs s}^{-1}) \) the spectral temperature increases with luminosity as in blackbody radiation, in the range of luminosities we studied, where thermal equilibrium is not achieved, the expected correlation is opposite (see Fig. 4). Such anti-correlations were, indeed, observed for SGR 1806-20 and SGR 1900+14 where the burst statistic is high enough (e.g., Feroci et al. 2001; Gogus et al. 2001; Ibrahim et al. 2001). This is encouraging, but a direct comparison of this data with results such as ours will require a more detailed analysis. In particular, the effects of strong magnetic fields have to be included. The observed periodic variations may be due to a rotation of a star with non-uniform surface temperature, while our result apply for isotropic emission. We hope to deal with this elsewhere.

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