Structure of pair winds from compact objects with an application to the emission from hot bare strange stars

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Abstract

A STATIONARY outflowing wind from the compact star consisting of electron-positron pairs and photons is studied. We do not not assume the thermal equilibrium, and include all two-body processes which occur in a such wind together with their radiative three-body variants. As an example, the wind injection source is a hot, bare, strange star. Such stars are thought to be powerful sources of hard X-ray photons and $e^{\pm}$ pairs created by the Coulomb barrier at the quark surface.

1. Introduction

WITTEN proposed what strange matter made from u, d, s quarks, e is the ground state of a matter with a lower energy per baryon [1]. For example, such matter can be in the early Universe at high $T = 100$–200 MeV. Witten's idea about the existence of such strange matter are not true due to the evaporation of such nuggets then Universe T downs to 10 MeV [2]. The Bodmer's proposal [3] about such matter at the gravitational star's core collapse is more preferable.

The properties of Strange Stars [4].

- Equation Of State $P \approx \frac{1}{3}(\rho - 4B)$, where B is the vacuum energy density. $\rho = 4 \cdot 10^{14}$ g cm^{-3} at the boundary in compare with $\rho = 0$ for neutron stars.
- $\frac{\partial M}{\partial \rho_c} > 0$ for all masses $0 < M \le M_{\max}$ instead of neutron stars. There are Strange stars with $M \to 0$. Really should be $A > 100$. The gravity is not important for such object. For Neutron Star $0.1M_{\odot} < M \le M_{\max}$. For Strange Star $\frac{\partial M}{\partial R} > 0$, while for Neutron Star $\frac{\partial M}{\partial R} < 0$.
- Typical Strange Stars $M \sim M_{\max} \sim 1.4$–$2M_{\odot}$, $R \sim 10$ km, T, I, cooling rates are similar to Neutron Stars. It is difficult to discover Strange Star.

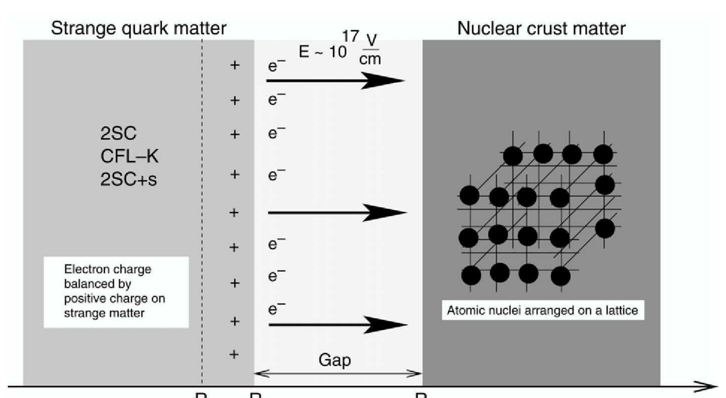

Figure 1: *A surface region of strange quark matter [5]. The region between $R \le r \le R_{\rm crust}$ is filled with electrons that are bound to strange matter but extend beyond its surface, R, leading to a deficit of electrons in the range $R_{\rm m} \le r \le R$ and therefore a net positive charge in the region. The associated electric field, $E \sim 10^{17}$ V cm^{-1} $> E_{\rm cr} = 1.3 \cdot 10^{16}$ V cm^{-1}, is sufficiently strong for avoiding contact between atomic matter and strange matter, enabling strange matter to be enveloped by ordinary atomic matter with mass $\sim 10^{-5}M_{\odot}$. 1 m^3 of such electrical field in the vacuum radiates as all stars of Universe.*

2. The Problem And The Method

1. In the Strange Star surface the pairs flux is huge in compare with the photons flux (Fig. 2). The star is boundary condition. The temperature of the surface T_S (or the energy flux in pairs L_e) is one parameter of the task.
2. We adopt typical Strange Star parameters $M = 1.4M_{\odot}$, $R = 10$ km.
3. It is possible to write and to solve Boltzmann kinetic equations for $e^{\mp}$, γ at $r \ge R$ to calculate the radiation from the star.
4. At the annihilation $e^{\mp}$ pairs gives 511 keV photons. Is it possible to investigate an annihilation line? Can we use this line as main feature to identify a bare strange star?

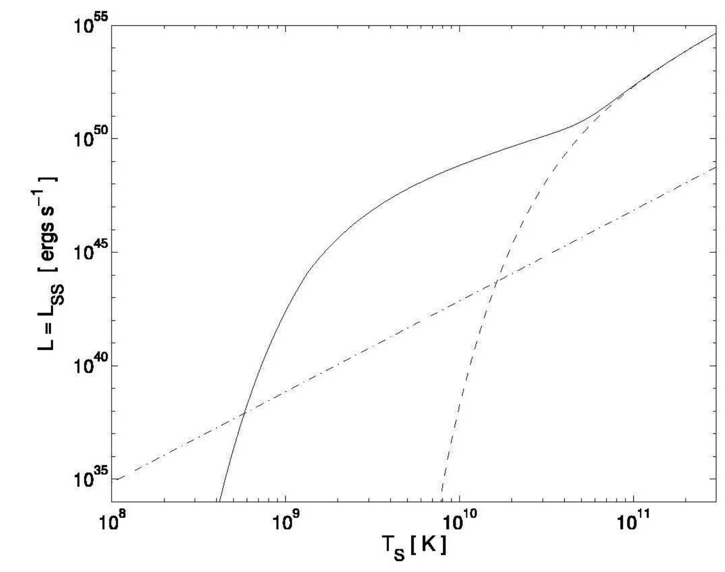

Figure 2: *Luminosities of a hot, bare, strange star in e^+e^- pairs (dotted curve), in thermal equilibrium photons (dashed curve), and the total (solid curve) as a functions of the surface temperature T_S [6], [7]. The upper limit on the luminosity in nonequilibrium photons, $L_{\rm neq} \lesssim 10^{-6}L_{bb}$, is shown by the dot-dashed curve, L_{bb} being the blackbody luminosity. The high plasma frequency suppresses waves with $\omega < \omega_p = \sqrt{\frac{8\pi\alpha}{3}\frac{n_u^2}{\rho_u}} \approx 20$ MeV. Pairs are generated by the supercritical electric field in free electrons states at $T > 0$.*

Table 1: *Included Physical Processes [8], [9], [10]*

Basic Two-Body Interaction	Radiative Variant
Møller and Bhaba scattering	*Bremsstrahlung*
$ee \to ee$	$ee \leftrightarrow ee\gamma$
Compton scattering	*Double Compton scattering*
$\gamma e \to \gamma e$	$\gamma e \leftrightarrow \gamma e e \gamma$
Pair annihilation	*Three quantum annihilation*
$e^+e^- \to \gamma\gamma$	$e^+e^- \leftrightarrow \gamma\gamma\gamma$
Photon-photon pair production	*Radiative pair production*
$\gamma\gamma \to e^+e^-$	$\gamma\gamma \leftrightarrow e^+e^-\gamma$

We consider the evolutionary spherically symmetric problem with the steady boundary condition till the receiving of the stationary solution [11], [12]. At low luminosity we use GR Boltzmann kinetic transport equations [13]

$$\frac{e^{-\phi}}{c}\frac{\partial f_i}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \mu e^{\phi}\beta_i f_i) - \frac{e^{\phi}}{p^2}\frac{\partial}{\partial p}\left(p^3 \mu \frac{\phi'}{\beta_i} f_i\right) - \frac{\partial}{\partial \mu}\left[(1-\mu^2)e^{\phi}\left(\frac{\phi'}{\beta_i} - \frac{\beta_i}{r}\right) f_i\right] = \sum_q (\bar\eta_i^q - \chi_i^q f_i).$$

We used the finite difference computational method to solve Bolzmann equations. We introduced the computational grid for phase space r, ϵ_e, μ. We replaced the space and angle derivatives by finite differences. We received the set of ODE's instead of System of Partial Differential Equations to solve. There are several characteristic times for different processes in the problem. The received system of ODE's is stiff. We used high-order implicit Gear's method [14] to integrate ODE's numerically. To solve the system of linear algebraic equations at every time step we used the cyclic reduction method.

For high luminosities $\ge 10^{44}$ ergs $\cdot$ s^{-1} it is possible to use hydrodynamical equations. Then $\gamma T(r) = \mathrm{const}$ [15], [16], [17]. We can estimate $\gamma T(R)$ from the Fig. 2. Then we know the average photons energy in the photosphere in the laboratory frame $3\gamma k_{\rm B}T(r_{\rm photo})$.

3. Results Of Calculations

1. The photon spectra in Fig. 3, 4 for different luminosities is a main result. Even at the photon's optical path $\tau_\gamma = 1$ ($L \approx 1 \cdot 10^{38}$ erg/s) the photon spectra is a stiff. The spectra contains the pairs annihilation line. The line width is defined by the surface temperature. Only at a bigger luminosity $L \gtrsim 1 \cdot 10^{40}$ erg/s then $\tau_\gamma \gg 1$ the spectrum becomes a soft due to 3 particles reactions.
2. Already for the low luminosity $\sim 10^{40}$ erg/s the photon's emission $L_\gamma(r = R)$ from the Strange Star with the layer deepness $\sim c/\omega_p$ [18], [19] can be considerable in compare with $L_{\mp}$ emission [12].
3. If the strange star surface photon radiation is low ($\lesssim 1 \cdot 10^{-8}L_{\rm bb}$), the photon spectra can give the information about the star mass because the readshift.
4. If the strange star surface photon radiation is high ($\sim 1 \cdot 10^{-6}L_{\rm bb}$), probably we can not see the annihilation line. In this case, where is the non-thermal part in the narrow range of luminosities, because of large sensitivity of pairs radiation from the temperature. This means next useful information. Let heated Strange Star is cooling. At high luminosity $L \gtrsim 10^{42}$ erg/s the stars spectra is near blackbody. At $10^{38} \lesssim L \lesssim 10^{39}$ erg/s we can see non-thermal part near the annihilation line. Below 10^{39} erg/s the spectra should be converted into the equilibrium spectra. So if we see such object, we know the approximate value of the luminosity and the distance.

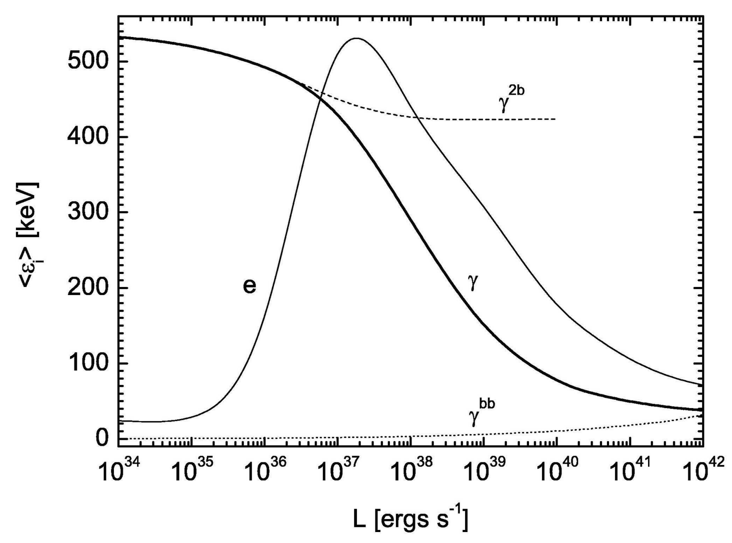

Figure 3: *Mean energy of the emerging photons (thick solid curve) and electrons (thin solid curve) as a function of the total luminosity [11]. For comparison, we show by the dotted curve the mean energy of blackbody photons for the same energy density as that of the photons at the photosphere. Also shown by the dashed curve the mean energies of the emerging photons in the case when only two-particles process are taken into account.*

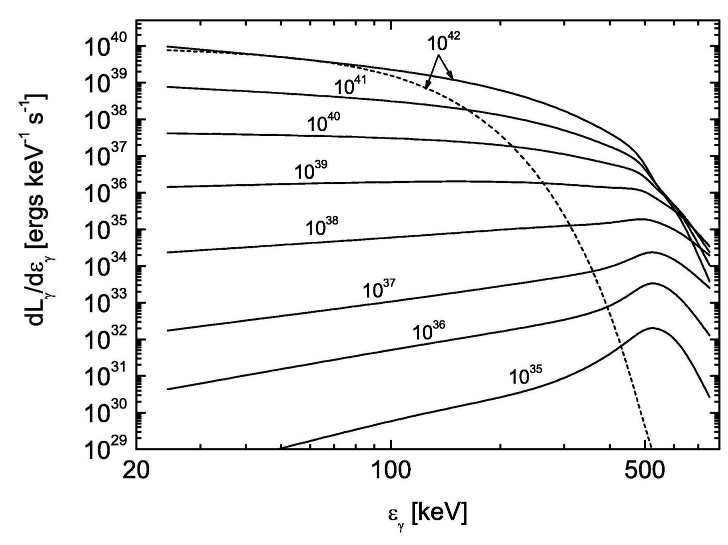

Figure 4: *Energy spectrum of emerging photons for different values of L as marked on the curves [11]. The dashed curve is the spectrum of blackbody emission.*

4. Experiments And Possible Applications Of Strange Stars

- Stars with the radius R less than the minimal radius of Neutron Star 10 km. Emission from binaries [20]. The isolated compact star with the black body radiation from known distance [5].
- The cooling of a newborn strange star differ from the cooling of a neutron star [5].
- Soft Gamma Repeaters (SGR) with super Eddington luminosity for Neutron Star $L_{\rm Edd} = 1.3 \cdot 10^{38}(M/M_{\odot})$ erg s^{-1} [5]. It is possible to explain the exitance of some "anomalous" SGR with the large luminosity, for example $\gtrsim 10^{42}$–10^{44} egr/s and a soft photon spectrum $\lesssim 100$ kev in compare with usual SGR [21], [22]. As we see Strange Star can eject photons with a huge luminosity, and a photon spectrum becomes softer at an increasing of a luminosity.
- We can't explain the narrow (some keV) annihilation line from the Galaxy center [23]. Although the amount of the detected e^+ flux is similar to the Strange Stars emission.

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