On Gaps Below Strange Star Crusts

- or how electric fields can sustain crusts close to neutron drip density above quark matter cores

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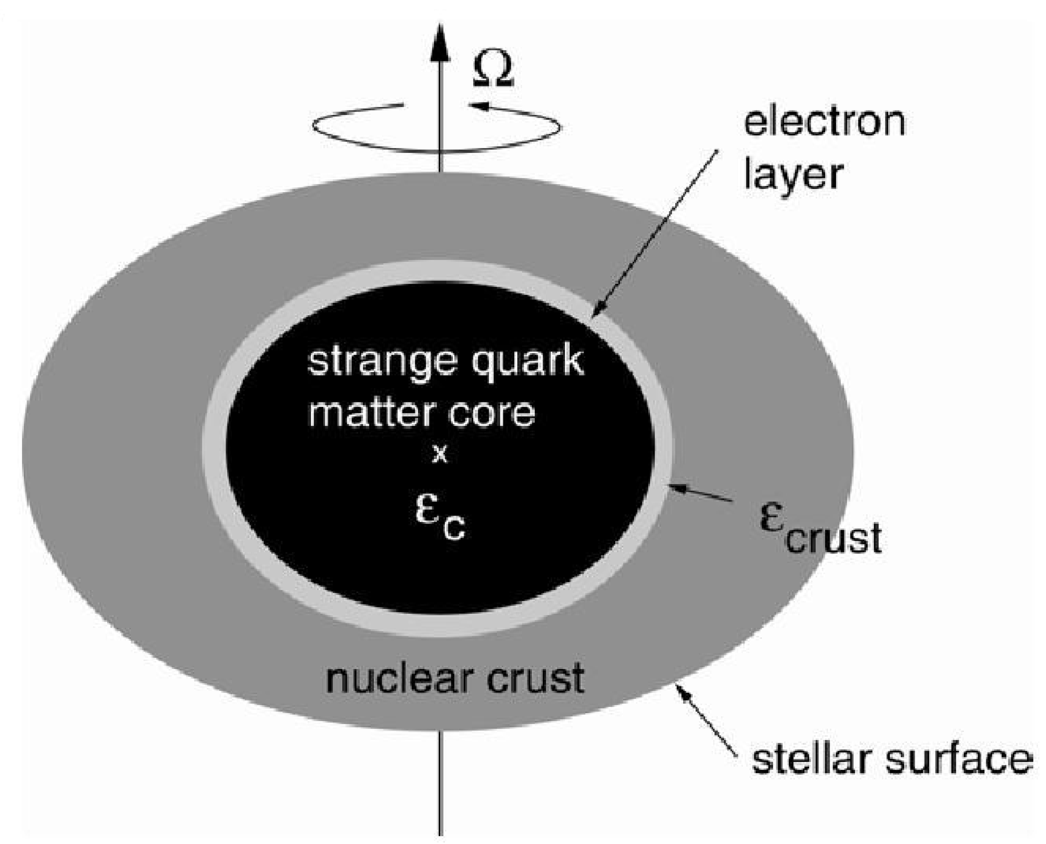
(1) Introduction

Strange matter is a bulk quark matter phase of roughly equal numbers of up, down and strange quarks with a smaller number of electrons to balance a slight deficit of the heavier strange quarks. The quark surface of a strange star may be very sharp – the density drops from above nuclear matter density to zero within a few fm. - and since the electrostatic force is weaker than the strong force confining the quarks, some of the electrons necessary to form a globally charge neutral object will create a thin electron atmosphere with a huge electric field of ~10^{17} V/cm outside the strange matter core. Even color-flavor locked quark matter which is neutral in bulk has an overall positive quark charge due to surface effects. The field is capable of sustaining a nuclear matter crust decoupled from the quark phase by an electron filled gap thought to be a few hundred fm. in size. The mass of such a crust is limited to approximately 10^{-5} $M_\odot$ by the neutron drip density, 4×10^{11} g/cm, where neutrons drip out of nuclei at the inner crust boundary and get dissolved in the quark phase. Smaller crust mass limits would result if the gap is sufficiently narrow to allow direct contact with the core or if there are significant quantum tunneling rates of nuclei into the core.



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The crust mass, radius and moment of inertia as well as the coupling with the strange core play important roles in the understanding of strange star properties, and therefore the properties of the gap are very important.

In this work we investigate the structure of the gap and the transition to the crust including the effects of gravity and temperature. We use a selfconsistent model which gives the details of the transition, and notably shows a new dependence on temperature.

It should be noted however that Jaikumar et. al (nucl-th/0507055) recently showed that, if the surface tension is not too large, a mixed fase of electons and quark nuggets may be favored near the surface, in which case the surface would be less sharp and neutral.

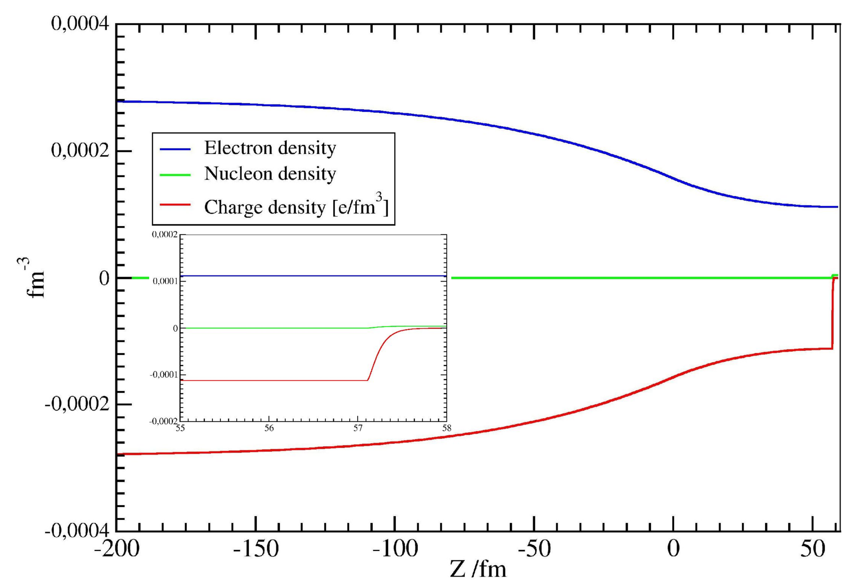
(2) Equilibrium of the Crust

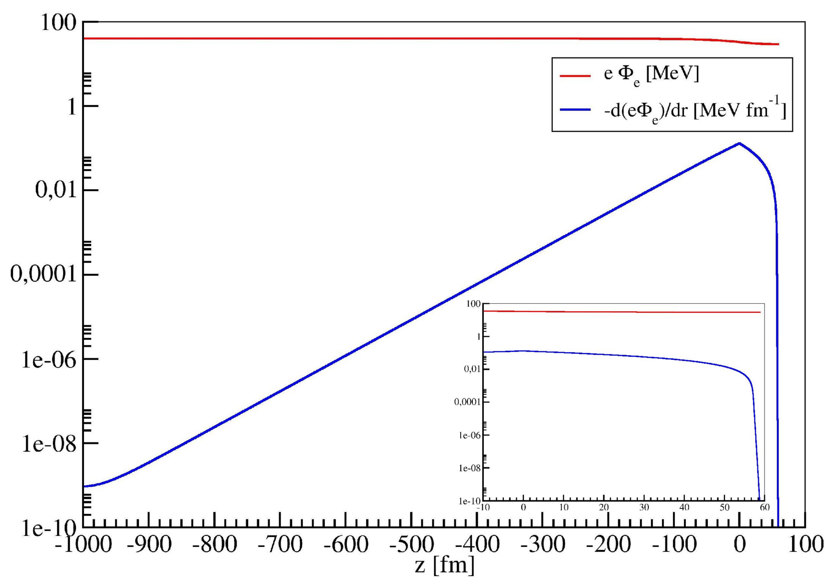
In a steady state the effective chemical potentials of electrons and nuclei should be constant to avoid migration. In particular they should be equal to their values at the top of the crust, *r=R*, where the electric field is zero and the chemical potentials are equal to the masses:

$$\mu_e^{eff} = \mu_e(r) - e\phi_e(r) + m_e\phi_g(r) = m_e + m_e\phi_g(R)$$
$$\mu_e(r) = m_e + m_e[\phi_g(R) - \phi_g(r)] + e\phi_e(r)$$
$$\mu_N^{eff} = \mu_N(r) + Ze\phi_e(r) + m_N\phi_g(r) = m_N + m_N\phi_g(R)$$
$$\mu_N(r) = m_N + m_N[\phi_g(R) - \phi_g(r)] - Ze\phi_e(r)$$

Here we include the effects of gravity through the (Newtonian) gravitational potential where most previous work only included the electrostatic potential. We do not include the effects of interactions between nuclei however and so can not describe the entire crust.

Using Poisson's equation in Newtonian gravity and treating the electrons and nuclei as Fermi gasses now leads to a system of four coupled first order differential equations in the chemical potentials and their derivatives, which may be solved numerically given boundary conditions in the charge neutral bulk of the strange core of non color flavor locked stars or at the surface of color flavor locked stars – we spare the reader the details. The graphs below display various properties as a function of distance above or below the surface of the quark core for a numerical solution reaching neutron drip density in the crust.



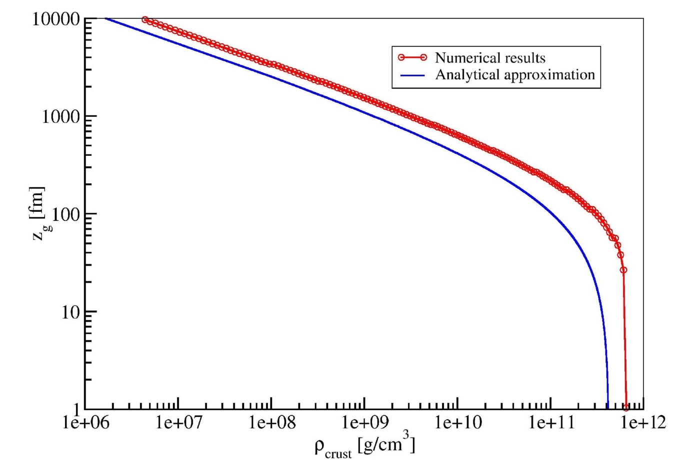


(3) Properties of the gap

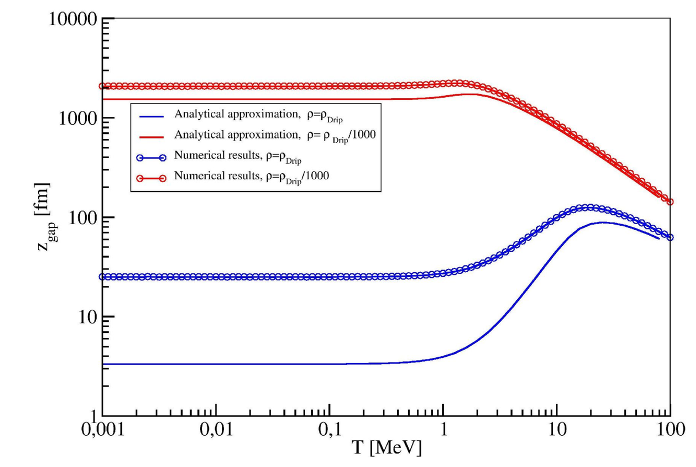
If we assume massless electrons and demand charge neutrality deep in the crust it becomes possible to solve analytically for the approximate position where nuclei first appear. For *T=0* the gap width then becomes:

$$z_{gap} = 170.5 \left(\frac{\rho}{\rho_D}\right)^{-1/3} \text{fm} - \frac{167 \text{ fm}}{e\phi_e(R_S)/30\text{MeV}}$$

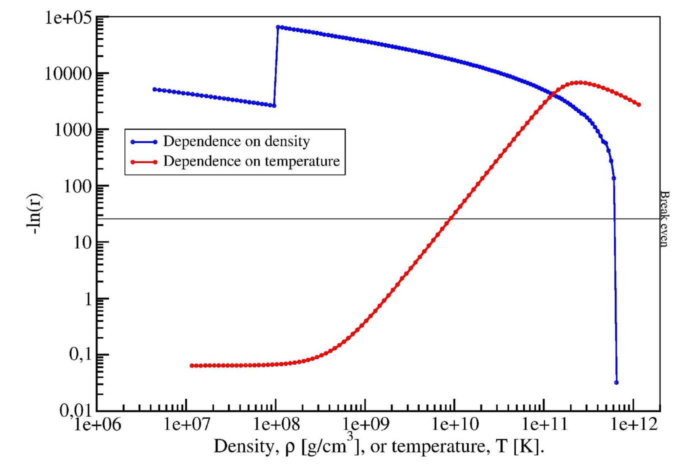
Where the density is scaled to the neutron drip density and the electric potential at the strange core surface to 30 MeV. The graph below compares this expression to numerical results.

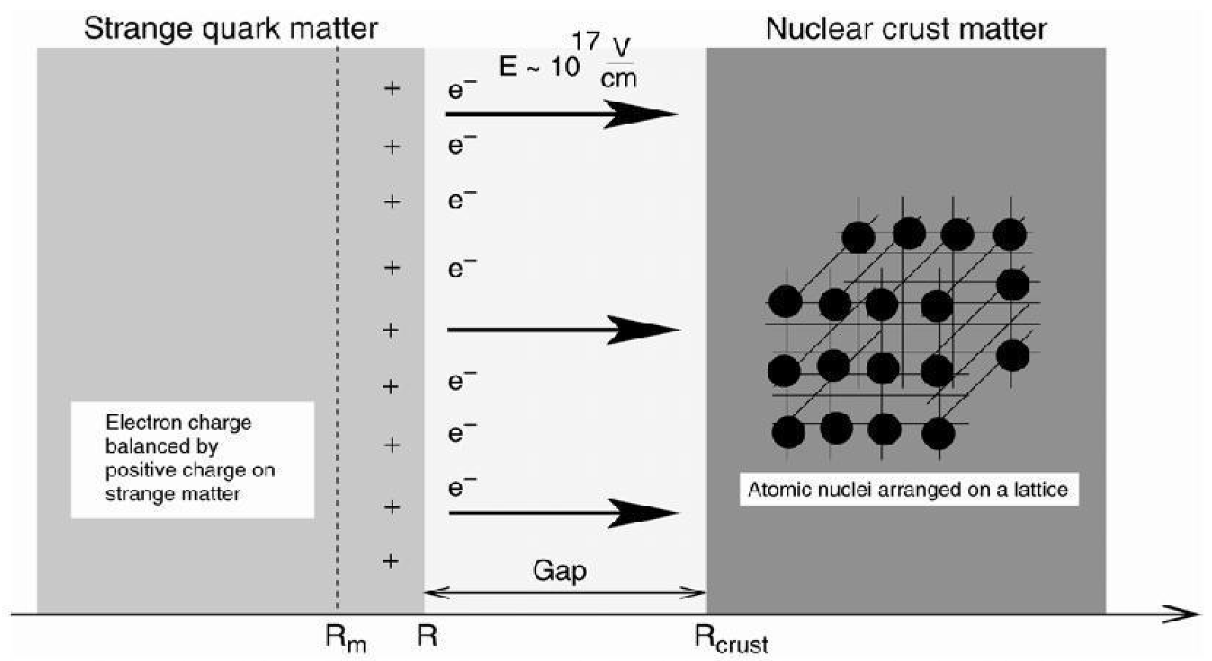


For finite temperatures a similar procedure can be used although the resulting expression can not be solved analytically. Note that the gap width actually increases at high temperatures before it decreases.



The transmission coefficient, *r*, for crust nuclei to penetrate the barrier can be estimated in the WKB approximation and is shown below. In an accreting star accretion and penetration would break even at $r \sim e^{-26}$.





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(4) Perspectives

Although it shows a new temperature dependence our model largely confirms previous work on the gaps below strange star crusts. However the detailed nature of the model allows us to make more confident estimates of properties such as the barrier transmission coefficient. This may in particular be interesting with respect to very heavy crusts approaching the limit of stability, such as it may happen in accreting strange stars. F. x. the luminosity of soft x-ray transients in quiescence likely depend on pycnonuclear reactions taking place around ~10^{12} g/cm^3 and likewise superburst most likely ignite at densities around ~10^9 g/cm^3 – both close to or above the maximum crust density in most scenarios. The processing of accreted matter crossing the gap thus opens up a powerfull new energy source in this important density range and would be interesting to investigate in detail.

Questions and comments, contact
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