Testing consistency of deconfinement heating of strange stars in superbursters and soft X-ray transients

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Abstract. Both superbursters and soft X-ray transients probe the thermal structure of the crust on compact stars and are sensitive to the process of deep crustal heating. It was recently shown that the transfer of matter from crust to core in a strange star can heat the crust by deconfinement and ignite superbursts provided certain constraints on the strange quark matter equation of state are fulfilled. Corresponding constraints are derived for soft X-ray transients in a simple parameterized model assuming their quiescent emission is powered in the same way, and the time dependence of this heating mechanism in transient systems is discussed.

1. Introduction

The possibility that strange stars may carry a small crust of ordinary nuclear matter separated from the quark matter phase by an electron filled gap is key to reconciling observed X-ray phenomenology in accreting binary systems with the strange quark matter hypothesis, because it allows deconfinement heating near the bottom of the crust to replace pycnonuclear reactions as the source of deep crustal heating needed to achieve observed inner temperatures. It was shown by Page & Cumming(2005) that accreting strange stars fulfilling a set of general constraints on the equation of state may thus achieve temperatures high enough to ignite superbursts over a broad range of parameters, and in Stejner & Madsen(2006) we recently considered the consistency of these constraints with observed surface temperatures of quiescent soft X-ray transients showing that such an approach may constrain the properties of strange quark matter further.

Superbursts – extremely long and energetic type I X-ray bursts (Kuulkers(2004) for an observational review) – are believed to originate in unstable carbon burning at densities around $10^8$ g cm$^{-3}$ (Cumming et al. 2005). For carbon to ignite at such densities the temperature must reach $6 \times 10^9$ K, and since superbursters all have similar accretion rates around $0.1 - 0.3 \dot{m}_{\text{Edd}}$, where $\dot{m}_{\text{Edd}}$ is the Eddington accretion rate, this gives an indication of the heat released as the accreted matter adjusts chemically to the increasing weight of the layers above. In neutron stars the majority of this heat ($\sim 1.4$ MeV/Nucleon) is released by pycnonuclear reactions beyond the neutron drip density (Haensel & Zdunik 1990, Haensel & Zdunik 2003, Brown et al.1998), but Cumming et al.(2005) found that even this may be insufficient to reach superburst ignition due to the neutrino emissivity associated with pair breaking and formation in superfluid neutron in the deep crust. The crust on a strange star is sustained electrostatically above the quark matter core and is therefore limited to the neutron drip density – and probably somewhat below this density due to tunneling of ions through the Coulomb barrier (Alcock et al. 1986, Stejner & Madsen 2005) This removes the neutrino emissivity from paired neutrons. Furthermore the deconfinement heating as matter is transferred from crust to core is potentially very powerful releasing a binding energy of $Q_{\text{SQM}} \lesssim 100$ MeV per nucleon, so accreting strange stars can potentially be hotter than neutron stars. This would depend however on the thermal conductivity, $K$, and neutrino emissivity, $\epsilon_\nu$, of the quark matter core which – although in principle directly calculable – depend on poorly constrained QCD-parameters. Hence superbursters actually constrain the relationship between the three core parameters, $Q_{\text{SQM}}$, $K$, and $\epsilon_\nu$, as shown by Page & Cumming(2005).

Soft X-ray transients are binary systems which go through long periods (years to decades) of relative quiescence with luminosities around $10^{32}$ erg s$^{-1}$ punctuated by short accretion outbursts giving time averaged accretion rates up to $10^{-10} M_\odot$ yr$^{-1}$. During quiescence the thermal radiation detected from the surface of some sources has been shown by Brown et al.(1998) to be consistent with with deep crustal heating by pycnonuclear reactions in neutron stars, but as for superbursters this would have to be replaced with deconfinement heating if the strange quark matter hypothesis holds true. Given a relationship between core and surface temperature and taking proper account of cooling by photon emission from the surface – which is more important for these cold systems – soft X-ray transients therefore probe the relationship between the core parameters in much the same way as superbursters.
2. Thermal structure model

The calculations are performed in a parameterized model, which although very simple has the virtues of allowing direct comparison and scaling between different systems and providing a physical insight easily lost in numerical modelling. This only allows a consistency check however and a more detailed model would be needed to strongly constrain the core parameters. The model is briefly summarized, but the reader is referred to Stejnær & Madsen (2006) for greater detail.

The thermal structure of the outer crust is discussed in detail in the literature – see e.g. Yakovlev et al. (2004) and a more detailed model would be needed for an isothermal core and

\[ \dot{m} Q_{\text{SQM}} = 1.8 \times 10^{-7} \dot{m}_{\text{SB}} Q_{\text{SQM}} T_{9}^{8} + \sigma T_{9}^{4} \]  

for an isothermal core and

\[ \dot{m} Q_{\text{SQM}} = \left( \frac{0.1}{0.7} \right)^{9/2} \dot{m}_{\text{SB}} Q_{\text{SQM}} T_{9}^{8} + \sigma T_{9}^{4}. \]

for a non-isothermal core. Here \( \dot{m} \) is the time averaged accretion rate in units of nucleons cm\(^{-2}\) s\(^{-1}\) and \( \dot{m}_{\text{SB}} \) is the accretion rate for superbursters.

3. Consistency with observations

Fig. 1 compares the temperatures derived above to observed soft X-ray transient surface temperatures including pure blackbody cooling, pure neutrino cooling from Eqs. 2 and 3 and the combined case in Eqs. 4 and 5. The observational sample is discussed in Stejnær & Madsen (2006) and consists of soft X-ray transients for which X-ray observations have determined both the surface temperature and accretion rate. The accretion rate is very uncertain however, so only thick bars are plotted, and for the three coldest sources only upper limits to the temperature have been established.

As may be seen in Fig. 1 photon cooling dominates at low accretion rates and for low binding energies, \( Q_{\text{SQM}} \). For warmer sources with high accretion rates or if the binding energy is high neutrino cooling dominates. No single curve can fit all the sources, but the heating mechanism discussed here, although unavoidable, may not be the only relevant source of heat – indeed the powerlaw components in the spectra of some of these sources are often taken to indicate residual accretion in quiescence – and so it only provides a minimum luminosity. The surface temperatures should therefore not fall significantly short of the of the temperature curves shown in Fig. 1 to be consistent with the core parameters required for superburst ignition at high accretion rates. Hence consistency of this model requires a very low binding energy below 1 MeV per nucleon.

It may be noted that Brown et al. (1998) similarly found that deep crustal heating of neutron stars could explain the quiescent emission from Cen X-4 if only 0.1 MeV of the energy released by pycnometal reactions per nucleon during an outburst was conducted into the core and deposited there. Yakovlev et al. (2003) and Yakovlev et al. (2004) instead interpreted Cen X-4 and SAX J1808.4-3658 as massive neutron stars with enhanced neutrino emission. In the context of strange stars the energy is deposited directly in the core, but no enhanced neutrino cooling is required if the quark matter binding energy, \( Q_{\text{SQM}} \), is small.

4. Time dependence of the heating mechanism

The model presented above used the time averaged accretion rate, but the accretion rate for soft X-ray transients.
Fig. 1. Left: comparing combined photon and neutrino cooling of an isothermal core (Eq. 4 with $\dot{n}_{SB} = 0.3 \dot{n}_{Edd}$) to observations with $Q_{SQM}$ as labelled for each curve. For reference curves with neutrino cooling only (Eq. 2) and photon cooling only are also shown. The curves assuming $Q_{SQM} = 100$ MeV and neutrino cooling only are nearly identical. For Cen X-4 the quoted temperature intervals overlap. Right: corresponding curves for a non-isothermal core.

is of course extremely time dependent, and if the transfer of matter from crust to core mirrors this time dependence such an approximation may not be adequate for all purposes. Modelling this in full here would go to far and only the time dependence of the heating mechanism (i.e. the tunneling rate of ions in the crust through the Coulomb barrier at the bottom of the crust) will be discussed, but one may be guided with respect to its consequences by similar considerations for neutron stars.

In neutron stars [Ushomirsky & Rutledge(2001)] found that following an accretion outburst the heat released by pycnonuclear reactions and electron captures higher in the crust forms distinct heat waves reaching the surface by diffusion. By analogy if the tunneling rate at the bottom of the crust – and hence the heating – is sufficiently time dependent following an accretion event, one would expect the qualitative conclusions in [Ushomirsky & Rutledge(2001)] to apply, leading to strong variations in the surface temperature following an outburst as the resulting heat waves reach the surface. In strange stars the heat is released at a lower density in the crust with a shorter diffusion time to the surface however, so the two heat waves may be closer in time.

Transfer of matter from the crust, with mass $M_C$, to the core by tunneling takes place at a rate of (Stejner & Madsen 2005)

$$\frac{dM_C}{dt} = -23.8 \frac{\rho_b}{\rho_D} \tau(\rho_b) M_\odot s^{-1}$$

(6)

where $\rho_b$ is the density at the bottom of the crust, $\rho_D = 7.8 \times 10^{11}$ g cm$^{-3}$ is the neutron drip density and $\tau$ is the transmission coefficient for ions striking the Coulomb barrier in their lattice motion. In [Stejner & Madsen(2005)] we discussed the structure of the gap between crust and core and found an expression for the transmission coefficient, which when inserted in Eq. 6 allows us to solve for crust mass and tunneling rate as functions of time for a given accretion scenario. One such solution is shown in Fig. 2 for a system with 10 day long accretion outbursts separated by quiescent intervals of 30 years and an average accretion rate of $1.9 \times 10^{-11}$ M$_\odot$ yr$^{-1}$ – roughly corresponding to Cen X-4. The integration is started with a crust mass sufficient low that the tunneling rate is negligible and the crust builds up until the mass transferred to the core during each cycle matches the average accretion rate. At this point the crust mass is at its maximum – as determined by the choice of Coulomb barrier height – during the accretion outbursts and then relaxes to a state with very little tunneling within about a year after each outburst. This is because the tunneling rate increases sharply with density near equilibrium, and means that practically all the heating will take place during or immediately after an
accretion outburst. Hence there will be heat waves similar to those found by Ushomirsky & Rutledge (2001) following an outburst, and these might be detectable in systems such as Cen X-4 where the recurrence time is very long (no outburst since 1969) allowing them to reach the surface before they are smeared out by the next outburst.

If – speculatively – strange stars are able to cool significantly on timescales comparable to the recurrence times for soft X-ray transients, it is also possible that the temperature will follow the tunneling rate more closely, and that the current tunneling rate late in an accretion cycle is therefore a better predictor for the temperature than the time averaged rate. For the solution in Fig. 2 and using Eq. 8 (neutrino cooling only) this actually predicts a surface temperature of 76 eV late in the cycle – just as observed for Cen X-4. To demonstrate the effect credibly would require detailed modelling beyond our scope here, but this does show the potential consequences: the need to keep \( Q_{\text{SQM}} \) small to explain such sources is reduced to the point that even neutrino emission alone could explain cold sources with long recurrence times. The coldest of them all, SAX J1808.4-3658, has a recurrence time of only 2 years however, so there the average accretion rate should be adequate casting doubt on the relevancy of such an argument.

5. Discussion

Using a simple scaling argument for the steady state temperature of accreting strange stars a consistency check was presented between the constraints on strange quark matter derived from superburst ignition conditions, and the temperature of quiescent soft X-ray transients – both assumed to derive from deep crustal heating by transfer of matter from crust to core.

We have seen that although the hottest soft X-ray transients most similar to superbursters are always consistent with superbursters, the colder sources require very low binding energy for strange quark matter below an MeV, unless the time dependence is more pronounced than would ordinarily be expected. This seems conspicuously fine tuned given that we are working with strong interaction energy scales, but no clear inconsistency could be shown.

In principle this simple model can go no further than this consistency check, but to demonstrate the method Fig. 3 shows how one might proceed to further constrain the quark matter properties. It shows the relations between the core parameters, which from Eqs. 2 and 3 must be fulfilled to reach superburst ignition and to explain Aql X-1 with neutrino cooling alone. Increasing the thermal conductivity one reaches \( K_{\text{crit}} \) at which point the core must be isothermal, so there are no common solutions between the isothermal curves. Hence the presence of an additional heating source for Aql X-1 must be assumed to render the constraints for this source irrelevant and all-lower solutions with low \( Q_{\text{SQM}} \) consistent with the colder sources. However even then we see from the superburst constraints that we would be limited to very low values of \( K \) and \( Q_{\nu} \) as well. Although the numerical values of these constraints could change significantly with more detailed modelling this shows the potential for such an approach to limit the possible range of core parameters and ultimately the range of QCD-parameters consistent with the strange quark matter hypothesis.

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References

Alcock, C., Farhi, E., & Olinto, A. 1986, ApJ, 310, 261
Brown, E. F., Bildsten, L., & Rutledge, R. E. 1998, ApJ, 504, L95
Cumming, A., Macbeth, J., in ’t Zand, J. J. M., & Page, D. 2005, [arXiv:astro-ph/0508432]
Gudmundsson, E. H., Pethick, C. J., & Epstein, R. I. 1983, ApJ, 272, 286
Haensel, P. & Zdunik, J. L. 1990, A&A, 229, 117
Haensel, P. & Zdunik, J. L. 2003, A&A, 404, L33
Kuulkers, E. 2004, Nuclear Physics B Proceedings Supplements, 132, 466
Page, D. & Cumming, A. 2005, ApJ, 635, L157
Stejner, M. & Madsen, J. 2005, Phys. Rev. D, 72, 123005
Stejner, M. & Madsen, J. 2006, [ArXiv:astro-ph/0603566]
Ushomirsky, G. & Rutledge, R. E. 2001, MNRAS, 325, 1157
Yakovlev, D. G., Levenfish, K. P., & Haensel, P. 2003, ApJ, 507, 265
Yakovlev, D. G., Levenfish, K. P., Potekhin, A. Y., Gnedin, O. Y., & Chabrier, G. 2004, ApJ, 417, 169