CHARTING THE TEMPERATURE OF THE HOT NEUTRON STAR IN A SOFT X-RAY TRANSIENT

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ABSTRACT

We explore the thermal evolution of a neutron star undergoing episodes of intense accretion, separated by long periods of quiescence. By using an exact cooling code we follow in detail the flow of heat in the star due to the time-dependent accretion-induced heating from pyro-nuclear reactions in the stellar crust, the surface photon emission, and the neutrino cooling. These models allow us to study the neutron stars of the Soft X-Ray Transients.

In agreement with Brown, Bildsten and Rutledge (1998) we conclude that the soft component of the quiescent luminosity of Aql X-1, 4U 1608-522, and of the recently discovered SAX J1808.4, can be understood as thermal emission from a cooling neutron star with negligible neutrino emission. However, we show that in the case of Cen X-4, despite its long recurrence time, strong neutrino emission from the neutron star inner core is necessary to understand the observed quiescent to outburst luminosity ratio. This result implies that the neutron star in Cen X-4 is much heavier than the one in the other systems and the pairing critical temperature $T_c$ in its center must be low enough (well below $10^8$ K) to avoid a strong suppression of the neutrino emission.

Subject headings: stars: neutron — X-rays: stars — dense matter — stars: individual (Aquila X-1, Cen X-4, SAX J1808.4-3658, 4U 1608-522)

1. INTRODUCTION

Neutron stars in Soft X-Ray Transients (SXRTs) undergo recurrent surges of activity separated by long phases of relative "quiescence". The detection of type I bursts during the substantial X-ray brightening observed in outburst ($\sim 10^{33-38}$ erg s$^{-1}$) unambiguously indicates that episodes of intense accretion onto the stellar surface do occur. The origin of the faint X-ray emission, observed in quiescence, at the level of $\sim 10^{32-33}$ erg s$^{-1}$, remains instead uncertain. Accretion as a power source (van Paradijs et al. 1987) cannot be excluded, however it would pose severe constraints on the spin period and magnetic field strength of the neutron star (Campana et al. 1998a). What appears to be more viable, as an energy source, is either thermal emission from the hot stellar interior (Brown et al. 1998) and/or shock emission from an enshrouded fastspinning pulsar (Stella et al. 1994; Campana et al. 1998b).

Brown, Bildsten and Rutledge (1998, referred to as BBR98 hereafter) showed, using simple but concrete arguments, that the "rock-bottom" emission, in quiescence, could result from the cooling of the neutron star made hot during the events of intense accretion: the inner crust compressed by the loaded material becomes the site of pyco-nuclear reactions that may deposit enough heat into the core to establish a thermal luminosity

$$L_q \sim \frac{Q_{\text{nc}}}{m_u} \langle \dot{M} \rangle \sim 6 \times 10^{32} \frac{\langle \dot{M} \rangle}{10^{-11} M_\odot \text{yr}^{-1}} \text{erg s}^{-1}$$

detected when accretion halts ($\langle \dot{M} \rangle$ is the time-averaged accretion rate, $Q_{\text{nc}} \sim 1.5$ MeV, the nuclear energy deposited per baryon, and $m_u$ the amu; Bildsten & Rutledge 2000).

Following this consideration, Rutledge et al. (1999, 2000) showed that accurate hydrogen atmosphere spectral models lead to emitting surfaces consistent with the neutron star radius, again pointing in favor of a thermal origin of the quiescent emission (or of part of it). The observation of an abrupt fading into quiescence in Aql X-1 (the prototype of a transient) with a sudden spectral hardening (Campana et al. 1998b; Zhang et al. 1998) remains however a challenge to the thermal hypothesis. A composite interpretation of the spectra and luminosities is still possible whereby the hard tail from the hidden pulsar coexists with the softer emission from cooling.

The interpretation of the quiescent emission seen in the four known soft X-ray transients, Aql X-1, Cen X-4, 4U 1608-522, EXO 0748-676 and in the transient X-ray 2.5 ms pulsar SAX J1808.4-3658 (Stella et al. 2000) gives, under the "cooling" hypothesis, the opportunity of probing the physics of the neutron star interior in an unprecedented way.

In this letter we study in detail the thermal evolution of transiently accreting sources with a full cooling code. We compute the "exact" quiescent luminosity and relate it to the accretion history. We then explore the consequences of the cooling hypothesis to infer properties of the underlying neutron star such as the presence of a superfluid in its core and the possibility of enhanced neutrino emission, in relation with its mass.

2. THE COOLING MODEL

We use an "exact" cooling code which solves the equations of heat transport and energy conservation in a wholly general relativistic scheme (Page 1989).

The cooling source is neutrino emission in both the crust (electron-ion bremsstrahlung, plasma and Cooper pair formation) and the core (modified Urca and neutron/proton bremsstrahlung, Cooper pair formation, and direct Urca in some cases), and surface photon emission. The heating source is accretion-induced production of nuclear energy: the heat released in the upper atmosphere by the infalling matter and in the envelope by thermonuclear burning is here neglected since it is rapidly radiated away and consequently does not affect the thermal evolution of the stellar interior (Fujimoto et al. 1987; Brown 2000). The heat sources located in the crust are instead
important (BBR98) and describe the readjustment, to chemical equilibrium, of the matter processed during the heavy accretion events. Energy released by electron captures and neutron emissions is included following Haensel & Zdunik (1990a) and proceeds at a rate proportional to the instantaneous (proper) accretion rate $\dot{M}_p(t)$. Pycnonuclear fusions, releasing the bulk of the energy, continue when the star is returning to its cooling state, since their characteristic time-scale ($t_{\text{py}} \sim$ months) is comparable to or longer than the duration of a typical outburst. This time lag is accounted for by introducing a heat release function

$$R_{\text{py}}(t) = \frac{1}{t_{\text{py}}} \int_0^t dt' \dot{M}_p(t') \frac{Q_{\text{py}}}{m_\text{n}} \exp[(t' - t)/t_{\text{py}}]$$

representing the energy deposited per unit time at the current time $t$ from the chain of pycnonuclear reactions ($Q_{\text{py}} = 0.86$ MeV/baryon). The inclusion of all the non-equilibrium energy sources (down to $\rho = 1.137 \times 10^{13}$ g cm$^{-3}$) assumes that the entire stellar crust has been replaced; this would take ~50 million years for a time averaged accretion rate of $10^{-11} M_\odot$ yr$^{-1}$ (Haensel & Zdunik 1990a). (Non-homogeneous stratification of nuclei due to non constant accretion is neglected.)

The temperature gradients in the interior determine how much of this heat is stored and how much immediately flows away to the surface. We calculate the thermal conductivity using the results of Baiko and Yakovlev (1995) in the crystallized crustal layers, Itoh et al. (1983), Mitake et al. (1984), and Flowers & Itoh (1980) in the liquid ones, and flowers & Itoh (1980) in the core. We use the calculations of Potekhin, Chabrier and Yakovlev (1997) for a cooling star with an accreted envelope to compute the surface thermal luminosity $L_{\text{surf}}$, i.e., the quiescent luminosity (visible in between outbursts) and the corresponding effective temperature $T_{\text{eff}}$, as a function of time.

[Diagram of critical temperatures $T_c$ vs $\rho$]

Fig. 1.— Critical temperatures $T_c$ for both proton $^1\text{S}_0$ and neutron $^1\text{S}_0$ and $^1\text{P}_2$ pairing assumed in his work. The central densities of the stars of various mass we study are indicated as well as the threshold for the direct Urca ("DURCA") process.

The chemical composition and the equation of state (EOS) of the crust are the ones of an accreted crust (Haensel & Zdunik 1990b) while for the core we follow Prakash, Ainsworth & Latimer (1988) using a compression modulus $K_0 = 240$ MeV and a symmetry energy dependence $\propto \rho^{0.7}$. With this particular EOS, the direct Urca process is allowed at densities $\rho > 1.28 \times 10^{15}$ g cm$^{-3}$, which are attained in neutron stars heavier than the critical mass $M_{\text{crit}} = 1.65 M_\odot$. Finally, we include the strong suppressing effects of superfluidity (neutron) and superconductivity (protons) on both the specific heat and neutrino emission: given the enormous uncertainty (Baldo et al. 1998) on the value of the critical temperature $T_c$ for $^1\text{P}_2$ neutron pairing we plot explicitly in Fig. 2 the values we adopt here. Generically we will refer to our 1.4 and 1.6 $M_\odot$ stars as slow cooling neutron stars and the 1.7 and 1.8 $M_\odot$ ones as fast cooling stars: the former ones have only the modified Urca process allowed in their core and suppression by neutron pairing is strong while the latter ones have the direct Urca process operating with suppression at lower temperatures so that fast neutrino cooling does affect significantly their thermal evolution.

3. TOWARD THE EQUILIBRIUM STATE

As a preliminary step we verify whether transient accretion on an initially cold neutron star is able to bring it to a hot stationary state and how fast this happens.

[Graph of $T_{\text{core}}$ vs $t$ (yr) after the onset of transient accretion, set at $t = 0$. The right scale reports the effective temperature $T_{\text{eff}}$ vs $t$.]

Fig. 2.— Redshifted core temperature $T_{\text{core}} (10^8 K)$ vs time $t$ (yr) soon after the onset of transient accretion, set at $t = 0$. The right scale reports the effective surface temperature as measured at infinity. The solid lines refer to a 1.4 $M_\odot$ superfluid star with transient accretion, $\Delta M = 6 \times 10^{-11} M_\odot$, $t_{\text{rec}} = 150$ days, and $t_{\text{out}} = 30$ days. The upper curve shows equilibration from a hotter state that may result from an early phase of steady accretion, whereas the lower curve mimics a resuscitating accretion episode following a phase of pure cooling. The thickness of the lines is because of the rapid variations due to accretion as can be seen in the inset where $T_{\text{core}}$ is plotted against time over a few cycles. The dot-dashed line shows the evolution of the same star with continuous accretion at $|\dot{M}| = 1.46 \times 10^{-10} M_\odot$ yr$^{-1}$.

For this, we model the transient accretion rate $\dot{M}(t)$ (as measured at infinity) with a fast exponential rise, on a time scale $t_{\text{rise}}$, reaching a maximum $\dot{M}_{\text{max}}$ followed by a power law decay of index $\alpha = 3$. Accretion is never turned off but becomes rapidly negligible in the power law decay phase. A new exponential rise recurs every $t_{\text{rec}}$. The rise time is set by the duration of the outburst phase $t_{\text{out}} = 3 t_{\text{rise}}$ which, for SXRTs is $\sim 30$ days long. The total accreted mass during one cycle $\Delta M = 1.08 t_{\text{rise}} M_{\text{max}}$ is the key parameter and is used to determine the value of $M_{\text{max}}$. We define the outburst luminosity (at infinity) $L_{\text{out}}$ such that the fluence is $L_{\text{out}} t_{\text{out}} = \eta \Delta M c^2$ with an

1We refer to the short review of Page (1998) for a general discussion of neutron star cooling and a description of the physical ingredients not specified here.
efficiency $\eta = 1 - e^{\phi}$, where $e^{\phi} = (1 - 2GM/Rc^2)^{1/2}$ is the redshift factor which is in between 0.15 to 0.30. The time averaged accretion rate is $\langle M \rangle = \Delta M/t_{\text{rec}}$.

We show in Fig. 3 an example of the heating (cooling) of an initially cold (hot) neutron star after the onset of intermittent accretion. It is compared with a model having constant accretion at a rate equal to $\langle M \rangle$. As expected, the star reaches thermal equilibrium and does it on a very short time scale $t_{\text{eq}} \sim 10^4$ yr, much shorter than any binary evolution time, and, in particular, much shorter than the time necessary to replenish the crust with fresh non catalyzed matter. The equilibration temperature is reached when the net injected heat is exactly balanced by the energy loss from the surface and/or from neutrino emission. In the insert we show the oscillations in the equilibrium core temperature occurring during each single outburst.

4. THE QUIESCENT LUMINOSITY

Our stars reach a hot equilibrium state and glow, in quiescence, at a luminosity $L_q$ which varies with $t_{\text{rec}}$ and $\Delta M$, as illustrated in Fig. 3. The solid lines refer to models with $\Delta M = 6 \times 10^{-11}M_\odot$, compatible with that inferred from the known transients Aql X-1, 4U 1608-52, and Cen X-4. For a 1.4 $M_\odot$ star we have also drawn the curve corresponding to a lower value of $\Delta M = 10^{-11}M_\odot$, that may describe the fainter transient SAX J1808.4.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3}
\caption{The quiescent luminosity versus the recurrence time resulting from our numerical calculations. The dashed area covers the region of the observed luminosity in SXRTs. The solid lines refer to a star accreting $\Delta M = 6 \times 10^{-11}M_\odot$ in each cycle. They are labelled by the mass of the star (in solar masses) and the existence (sf) or non existence (nsf) of a superfluid phase. The dot-dashed line shows our results for 1.4 $M_\odot$ superfluid star loading $\Delta M = 10^{-11}M_\odot$ in each cycle.}
\end{figure}

Essentially, the same equilibration luminosities $L_q$ are found using either transient accretion or the equivalent averaged rate. $L_q$ depends crucially on whether fast neutrino emission in the inner core is allowed or inhibited, as illustrated in Fig. 3.

For slow cooling stars with superfluidity (upper solid lines ‘1.4sf’ and ‘1.6sf’), neutrino emission is totally suppressed and the equilibrium temperature is determined by balance of nuclear heating with photon cooling. When superfluidity is not included, the stars are slightly less luminous as there is a small leakage of neutrinos due to the inefficient modified Urca process; the difference is small and we omit the results in the figure. In these cases with a fixed accreted mass $\Delta M$ per cycle we see that, naturally, $L_q$ is inversely proportional to $t_{\text{rec}}$.

When fast neutrino emission is allowed (‘1.7sf’ and ‘1.8sf’ lines), the equilibration temperature is much lower and the lowest $L_q$ are obtained in the case neutrino emission is not affected by neutron pairing (‘1.8nsf’ case). In these fast cooling models the dependence of $L_q$ on $t_{\text{rec}}$ is much weaker than in the slow cooling cases since most of the heat deposited during an accretion cycle is rapidly lost into neutrinos. This is similar to what happens in cooling isolated neutron stars: the star’s temperature is almost entirely controlled by the value of $T_c$ (Page & Applegate 1992). If $T_c$ were very high at the center of even our most massive stars, then neutrino emission would be completely suppressed and the evolution of the superfluid 1.8 $M_\odot$ star would be almost identical to the superfluid 1.4 $M_\odot$ star. We explicitly choose a relatively low $T_c$ at high density to allow heavier stars (1.7 and 1.8 $M_\odot$ in our specific model) to have a qualitatively different behaviour relative to the less massive ones.

5. COMPARISON WITH DATA

The most convenient quantity for comparison with data is the ratio $F$ of fluence in quiescence $L_q/t_{\text{rec}}$ to fluence in outburst $L_\text{out}/(t_{\text{out}} \sim \Delta M t_c^2)$ (BBR98). This gives us a direct measurement of the fraction $f$ of the heat released in the crust during accretion which is stored in the stellar interior and later slowly leaking out to the surface

$$F = \frac{L_q}{L_\text{out}/t_{\text{out}}} = f \frac{Q_{\text{flu}}}{m_\nu c^2} e^{-\phi} \eta$$

Our exact cooling code computes $L_q$ and thus predicts $f$. This is illustrated in Fig. 4 where we give model values for $L_q/L_\text{out}$ against $t_{\text{rec}}/t_{\text{out}}$ and where we draw the theoretical line $f = 1$ of Eq. 3 for 1.4$M_\odot$ and 1.8$M_\odot$ stars. Our numerical results when neutrino emission is negligible (“1.4sf” solid line) are very close to the $f = 1$ line showing a heat storage efficiency almost independent of $t_{\text{rec}}/t_{\text{out}}$. The ratio $L_q/L_{\text{out}}$ is dramatically reduced when direct Urca emission switches on, as in the core of our heavier stars (“1.7sf” and “1.8sf” solid lines). In these cases, the heat storage efficiency decreases with decreasing $t_{\text{rec}}/t_{\text{out}}$ (along a line of given mass): the neutron star in a transient with shorter $t_{\text{rec}}$ has a warmer core and an enhanced neutrino emissivity ($\propto T_c^6$) leading to a lower value of $f$.

Rutledge et al. (2000) analysed the observation of five SXRTs, Aql X-1, Cen X-4, 4U 1608-52, EXO 0748-767, and the Rapid Burster, made in their quiescent state, i.e. during the observed periods of lowest emission. Fitting the spectra with H atmospheric models they calculated the thermal luminosity $L_q$ and the luminosity $L_{\text{out}}$ time averaged over an outburst. They all display similar peak luminosities and outburst times. For the fainter source SAX J1808.4 this analysis is not available; we took $L_q = 2.5 \times 10^{32}$ erg s$^{-1}$, $L_{\text{out}} = 10^{35}$ erg s$^{-1}$, $t_{\text{out}} = 20$ days and $t_{\text{rec}} = 700$ days (Stella et al. 2000).

Overlying all these observations in the diagram of Fig. 4, it appears remarkable that Aql X-1 and 4U 1608-52 stands just on the theoretical line constructed for 1.4 $M_\odot$ (close also to 1.6 $M_\odot$ as shown in Fig. 3). Cen X-4 is adjacent to the 1.8 $M_\odot$ model star results, i.e., requires the occurrence of fast neutrino cooling (alternatively, a value of $f < 1$ may result from a crust only partially replaced). The Rapid Burster would fit the theory if it mass lied in an intermediate range with fast neutrino emission strongly controlled by pairing.
Having calculated the upper theoretical bound \((f = 1)\) on the efficiency of the rediffusion of the pycnonuclear energy, we can interpret the peculiar behaviour of EXO 0748−767 as due to an extra luminosity resulting from the gravitational energy released by a faint accretion and/or by the interaction of the infalling matter with the magnetosphere (propeller) \((\text{BBR}98)\).

Our results confirm the overall picture suggested by Brown et al \((\text{BBR}98)\) in their parametric approach: the quiescent luminosity seen in SXRTs comes from the rediffusion toward the surface of the heat deposited in the core by the pycnonuclear reactions triggered in the crust due to transient accretion.

![Graph showing the relationship between luminosity ratio and recurrence time](image)

**Fig. 4.** Quiescent to outburst luminosity ratio plotted versus the ratio of the recurrence time over the outburst time. Bold solid lines are the results of our numerical calculations as in Fig. 3. The expected results for \(f = 1\), see Eq. \(6\), are shown for our 1.4 \(M_\odot\) star (dashed-dot line) and 1.8 \(M_\odot\) star (dashed line). The filled squares represent the observed values. In the case of Cen X-4 there is still some uncertainty about the value of \(t_{\text{rec}}\).

6. **WEIGHTING NEUTRON STARS AND PROBING SUPERFLUIDITY**

We can now use our results to infer properties of the star in a transient through the comparison with the data.

The mass signature in the \(L_q/L_{\text{out}}\) vs \(t_{\text{rec}}/t_{\text{out}}\) plot is mainly determined by the state of the matter in the inner core of the neutron star. The clear drop in the ratio \(L_q/L_{\text{out}}\) when the source mass is above the critical mass for fast neutrino emission \(M_\text{cr} (= 1.65 M_\odot\) in our particular model) permits us to discriminate, in principle, between stars with mass close to the canonical values \((1.4 M_\odot)\) and more massive objects. In this context, the estimated ratio \(L_q/L_{\text{out}}\) of Cen X-4 \((\text{BBR}98)\) can be easily explained if its neutron star is heavier than the one in the other observed SXRTs. The most accurate measurements of neutron star masses cluster around 1.4 \(M_\odot\) \((\text{Thorsett} \& \text{Chakrabarty} 1999)\), but they refer to objects in NS+NS systems which are thought to have accreted only a tiny amount of mass \((0.001\) to 0.01 \(M_\odot)\). On the contrary, current observational capabilities do not severely constrain the mass \((\text{whose observed range, including uncertainties, varies between 1.4 and 1.9 \(M_\odot)\) of those neutron stars belonging to the low mass systems composed of a millisecond pulsar and a white dwarf companion \((\text{the probable descendent of the SXRTs})\). In these binaries, the neutron star could have undergone a substantial load of matter \((0.1\) to 0.5 \(M_\odot)\) while being spun up. In effect, there is an increasing observational evidence \((\text{Casares et al. 1998})\) and theoretical arguments \((\text{Stella \& Vietri 1999; Possenti et al. 1999; Heyl 2000})\) suggesting that the rapidly spinning stars can be significantly more massive than the slowly rotating population.

Combining the observed ratio \(L_q/L_{\text{out}}\) with future independent measurements of the mass of the neutron stars in the SXRTs, one could infer an upper limit on the critical pairing temperature \(T_c\). Notice, however, that many other fast neutrino emission channels, beside the simplest nucleon direct Urca considered here, are possible as, for example, direct Urca processes involving hyperons of deconfined quark matter. The constraints we could obtain about the value of \(T_c\) may then well refer to hyperon or quark pairing \((\text{Page et al. 2000})\).

Charting the temperature of the old hot neutron star in a soft X-ray transient is hence a valuable tool to investigate dense matter in neutron star cores which is complementary to the study of isolated young cooling neutron star. It moreover opens the possibility to study the interior of stars which can be more massive than the isolated ones.

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