Neutron star cooling in transiently accreting low mass binaries: a new tool for probing nuclear matter

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Abstract. We explore, using an exact cooling code, the thermal evolution of a neutron star undergoing episodes of intense accretion, alternated by long periods of quiescence (e.g. Soft X-Ray Transients; SXRTs hereon). We find that the soft component of the quiescent luminosity of Aql X-1, 4U 1608-522 and of SAX J1808.4-3658 can be understood as thermal emission from a cooling neutron star with negligible neutrino emission. In the case of Cen X-4 strong neutrino emission from the inner core is necessary to explain the observation: this may indicate that the neutron star of Cen X-4 is heavier than 1.4 M\(_\odot\). This study opens the possibility of using the quiescent emission of SXRTs as a tool for probing the core superfluidity in relation to the mass of the neutron star.

1. Introduction

The neutron stars (NSs) of the SXRTs undergo recurrent surges of X-ray activity (due to intense accretion onto the stellar surface) separated by longer periods of relative quiescence. The quiescent emission, around 10^{32–33} erg s\(^{-1}\), is characterized by a thermal spectrum plus a power law tail at higher energies. Though accretion can not be excluded as energy source (van Paradijs et al. 1987), observations hint in favor of interpreting the thermal component as due to the cooling of the old NS, heated during the episodes of intense accretion (Brown, Bildsten & Rutledge 1998, BBR98 hereafter; Rutledge et al. 2000; Campana et al. 1998). Freshly accreted matter undergoes nuclear burning (Brown 2000) whose energy is almost instantly lost through the photosphere. As accretion proceeds recurrently, the NS envelope becomes progressively enriched of Fe elements. The old crust is eventually assimilated into the core and the NS, after a few million years,
is endowed by a new crust of non-equilibrium matter which is approaching its lowest energy state through a sequence of pycnonuclear reactions (Haensel & Zdunik 1990a, 1990b). The heat, deposited deeply into the crust, emerges in quiescence with a luminosity $L_q$ (visible between outbursts), depending on the balance between photon and neutrino cooling with pycnonuclear heating. We here calculate $L_q$ with an exact cooling code to derive the upper theoretical bound on the efficiency of rediffusion of the pycnonuclear energy as function of the recurrence time of a SXRT. We will also prove that charting the temperature of the old hot NS in a SXRT is a valuable tool to investigate the properties of nuclear matter in its core, in alternative to the study of isolated young cooling NSs. As some of these compact objects may have accreted a substantial amount of mass from the companion (Burderi et al. 1999), this study opens also the possibility to explore the interior of NSs which can be more massive than the isolated ones. As an illustration of this approach we compare the results of our calculation with the observation of the quiescent emission seen in some SXRTs (Aql X-1, Cen X-4, 4U 1608-522, EXO 0748-676, Rapid Burster) and in the transient X-ray 2.5 ms pulsar SAX J1808.4-3658. The agreement between theory and observation is quite remarkable.

2. Modeling cooling and transient accretion

We use an exact cooling code which solves the equations of heat transport and energy conservation in a wholly general relativistic scheme (Page 1998). The cooling sources are neutrino emission (in the crust and the core) and surface photon radiation. The heating source is accretion-induced production of nuclear energy: in a fully replaced crust, the bulk of the energy is released by the pycnonuclear fusions ($Q_{py} \sim 0.9$ MeV/baryon) in a time-scale $t_{py} \sim$ months.

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 & Lattimer (1988). We include the strong suppressing effects of superfluidity (neutron) and superconductivity (protons) on both the specific heat and neutrino emission.

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1 The thermal conductivity is as in Colpi et al. (2001). We use the calculations of Potekhin, Chabrier and Yakovlev (1997) for a cooling star with an accreted envelope to compute $L_q$ and the corresponding effective temperature $T_{eff}$.

2 We use a heat release function

$$R_{py}(t) = \frac{1}{t_{py}} \int_0^t dt' M_p(t') \frac{Q_{py}}{m_u} \exp[(t' - t)/t_{py}]$$

representing the energy deposited per unit time at the current time. A minor energetic contribution comes from electron captures and neutron emissions (Haensel & Zdunik 1990a) occurring at a rate proportional to the instantaneous accretion rate $M_p(t).m_u$ is the atomic mass unit.

3 Generically, stars with mass $1.4 \rightarrow 1.6$ $M_\odot$ have only the modified Urca process allowed in their core and suppression by neutron pairing is strong, while stars with $1.7 \rightarrow 1.8$ $M_\odot$ have the direct Urca process operating with suppression at lower temperatures so that fast neutrino cooling does affect significantly their thermal evolution.
Figure 1. a. Redshifted core temperature $T_{\text{core}} (10^8 \text{ K})$ 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 upper curve shows equilibration from a hotter state that may result from an early phase of steady accretion, whereas the lower curve mimics a resurrecting 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 insert where $T_{\text{core}}$ is plotted against time over a few cycles. b. The quiescent luminosity versus the recurrence time from our calculations. The dashed area covers the region of the observed luminosity in SXRTs. The solid lines refer to a star accreting $\Delta M = 6 \times 10^{-11} M_\odot$ per cycle (compatible with that inferred from the transients Aql X-1, 4U 1608-522 and Cen X-4). They are labeled 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 $\Delta M = 10^{-11} M_\odot$ (it may describe the fainter transient SAX J1808.4-3658).

We model the transient accretion rate $\dot{M}(t)$ (measured at $\infty$) with a fast exponential rise, on a time scale $t_{\text{rise}} \sim 10$ days, reaching a maximum $\dot{M}_{\text{max}}$, followed by a power law decay of index $\alpha = 3$. Accretion is never turned off but becomes negligible at $t_{\text{out}} = 3t_{\text{rise}} \sim 30$ days (a typical duration $t_{\text{out}}$ of the outbursts in SXRTs). A new exponential rise recurs every $t_{\text{rec}}$. Thus, the total accreted mass during one cycle is $\Delta M = 1.08t_{\text{rise}} \dot{M}_{\text{max}}$; the time averaged accretion rate is $\langle \dot{M} \rangle = \Delta M/t_{\text{rec}}$; and the outburst luminosity (at $\infty$) $L_{\text{out}}$ is such that the fluence $L_{\text{out}} t_{\text{out}} = \eta \Delta M c^2$, with $\eta$ the efficiency.

3. Equilibrium temperature and quiescent luminosity

We show in Fig. 1a 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 (dot-dashed line) having constant accretion at a rate equal to
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Figure 2. 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. 1b. The filled squares represent the observed values. In the case of Cen X-4 there is still some uncertainty about the value of $t_{\text{rec}}$. The peculiar behavior of EXO 0748-767 can be due to an extra luminosity resulting from the energy released by a faint accretion and/or by the interaction of the infalling matter with the magnetosphere (BBR98).

$\langle \dot{M} \rangle = 1.46 \times 10^{-10} \, M_\odot \, \text{yr}^{-1}$. The star reaches thermal equilibrium on a time scale $\tau_{\text{equ}} \sim 10^4 \, \text{yr}$, much shorter than any binary evolution time, and also much shorter than the time necessary to replenish the crust with fresh non catalyzed matter. The equilibration temperature is attained when the net injected heat is exactly balanced by the energy loss from the surface and/or from neutrino emission. Fig. 1b shows that $L_q$ depends crucially on whether fast neutrino emission in the inner core is allowed or inhibited (and in turn on the value of the critical temperature $T_c$ for both proton and neutron pairing). For $1.4 - 1.6 \, M_\odot$ 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 (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 proportional to $1/t_{\text{rec}}$. When fast neutrino emission is allowed (‘1.7sf’ & ‘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’). In these fast cooling models the dependence of $L_q$ on $t_{\text{rec}}$ is weak since most of the heat deposited during a cycle is rapidly lost into neutrinos.

4. Comparison with the data as a tool for probing NS properties

In Fig. 2 we compare the results of our calculation with the ratios $L_q/L_{\text{out}}$ and $t_{\text{rec}}/t_{\text{out}}$ observed in 6 SXRTs (Rutledge et al. 2000; Stella et al. 2000). It
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appears remarkable that Aql X-1 and 4U 1608-52 stands just on the theoretical line constructed for 1.4 M☉-star, thus strongly supporting the hypothesis that the quiescent luminosity \(L_q\) 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 (BBR98). \(f\) is the fraction of the heat released in the crust during accretion which is stored in the stellar interior and later slowly leaking out to the surface: the expected results for \(f = 1\), are shown for our 1.4 M☉-star (dashed-dot line) and 1.8 M☉-star (dashed line). It appears that \(f \ll 1\) when direct Urca emission switches on, as in the core of our heavier stars (‘1.7sf’ and ‘1.8sf’, solid lines). In these framework we can now use our results to infer properties of the neutron star. For example, the measured ratio \(L_q/L_{\text{out}}\) of Cen X-4 may be explained if its NS is heavier than the canonical 1.4 M☉. The Rapid Burster would fit the theory if its mass lies in an intermediate range. Measuring the masses of SXRTs by charting the X-ray temperature may provide a clue for establishing the link between the NSs in low mass binaries and the millisecond pulsars (Stella et al. 1994). More concretely, combining the observed ratio \(L_q/L_{\text{out}}\) with future independent measurements of the mass of the NSs in the SXRTs, one could pose constraints on the value of the critical temperature for neutron pairing \(T_c\) (Page et al. 2000).

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