CRUSTAL HEATING AND QUIESCENT EMISSION FROM TRANSIENTLY ACCRETING NEUTRON STARS

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ABSTRACT

Nuclear reactions occurring at densities \( \approx 10^{12} \) g cm\(^{-3} \) in the crust of a transiently accreting neutron star efficiently maintain the core at a temperature \( \approx (5-10) \times 10^7 \) K. When accretion halts, the envelope relaxes to a thermal equilibrium set by the flux from the hot core, as if the neutron star were newly born. For the time-averaged accretion rates \( (\approx 10^{-10} M_\odot \text{ yr}^{-1}) \) typical of low-mass X-ray transients, standard neutrino cooling is unimportant and the core thermally reradiates the deposited heat. The resulting luminosity is \( \approx 5 \times 10^{32} \) ergs s\(^{-1} \) and agrees with many observations of transient neutron stars in quiescence. Confirmation of this mechanism would strongly constrain rapid neutrino cooling mechanisms for neutron stars (e.g., a pion condensate). Thermal emission had previously been dismissed as a predominant source of quiescent emission since blackbody spectral fits implied an emitting area much smaller than a neutron star’s surface. However, as with thermal emission from radio pulsars, fits with realistic emergent spectra will imply a substantially larger emitting area. Other emission mechanisms, such as accretion or a pulsar shock, can also operate in quiescence and generate intensity and spectral variations over short timescales. Indeed, quiescent accretion may produce gravitationally redshifted metal photoionization edges in the quiescent spectra (detectable with AXAF and XMM). We discuss past observations of Aql X-1 and note that the low-luminosity (less than \( 10^{34} \) ergs s\(^{-1} \)) X-ray sources in globular clusters and the Be star/X-ray transients are excellent candidates for future study.

Subject headings: accretion, accretion disks — stars: neutron — stars: individual (Aquila X-1, SAX J1808.4–3658)

1. INTRODUCTION

The temperature of an accreting neutron star’s core and crust is a subject of much current interest, both for magnetic field evolution studies and thermonuclear burning (Brown & Bildsten 1998 and references therein). For neutron stars (NSs) that steadily accrete at \( M \approx 10^{-11} \) to \( 10^{-9} M_\odot \text{ yr}^{-1} \), balancing the recurrent heating from thermally unstable hydrogen/helium burning with the cooling from neutrino emission and radiative diffusion requires core temperatures of \( T_c = (1-2) \times 10^7 \) K (Ayasli & Joss 1982; Hanawa & Fujimoto 1984). For these accretion rates, no more than a few percent of the hydrogen/helium burning luminosity diffuses inward and heats the core (Fujimoto et al. 1984, 1987). There is an additional luminosity in the inner crust (densities above neutron drip, \( \approx 5 \times 10^{11} \) g cm\(^{-3} \)), where the compression of matter by accretion induces electron captures, neutron emissions, and pyconvonuclear reactions that release \( Q_{\text{core}} \approx 1 \) MeV/\( m_p \) \( \approx 10^{18} \) ergs g\(^{-1} \) (Haensel & Zdunik 1990). These reactions send most of their heat into the core and therefore play a more important role in maintaining the interior thermal balance of a constantly accreting neutron star (Miralda-Escudé, Paczynski, & Haensel 1990; Bildsten & Brown 1997; Brown & Bildsten 1998).

For the case of transient accretors, the heating of the interior is not so simple. Most of the heat released by hydrogen/helium burning in the upper atmosphere leaves immediately during the unstable burning (Hanawa & Fujimoto 1986; Fujimoto et al. 1987). Moreover, the time between accretion outbursts is much longer than the cooling time of the NS atmosphere. As a result, H/He burning alone cannot heat the core to the interior temperatures of a steadily accreting star. This is an important point, since thermal emission from transiently accreting NSs would be observable when accretion halts, if the core were sufficiently hot (van Paradijs et al. 1987; Verbunt et al. 1994; Asai et al. 1996b; Campana et al. 1998a).

In this Letter, we show that direct nuclear heating in the deep neutron star crust heats the interior much more strongly and naturally explains a large fraction of the quiescent emission seen from transient NSs. During each outburst, the heat released from the crustal reactions flows into the core and maintains it at \( T_c \approx 10^7 \) K (Bildsten & Brown 1997). Once the core is in steady state, the heat radiated during quiescence must equal the fraction of the heat deposited during the outburst. As we show in § 2, in quiescence the NS then emits a time-averaged luminosity \( \sim (1 \text{ MeV}/m_p)(\langle M \rangle \sim 6 \times 10^{32} \) ergs s\(^{-1} (\langle M \rangle/10^{-11} M_\odot \text{ yr}^{-1}) \). For time-averaged (we here mean over the recurrence interval) accretion rates of \( \langle M \rangle \approx 10^{-10} M_\odot \text{ yr}^{-1} \), this amount of thermal emission is unavoidable unless the neutrino cooling is much more rapid than the standard mechanisms we considered.

Of the NS transients detected in quiescence, most have a luminosity \( L_q \sim 10^{33} \) ergs s\(^{-1} \), and the ratio of outburst to quiescent fluence is constant to within a factor of \( \approx 10 \) (Chen, Shrader, & Livio 1997). The rough agreement between our estimate and observed values of \( L_q \) gives new impetus for a thermal interpretation of the quiescent emission. As we discuss in § 3, spectral fits with realistic emergent spectra will show an increase in the emitting area over blackbody fits (as in radio pulsars; Rajagopal & Romani 1996; Zavlin, Pavlov, & Shibanov 1996). This alleviates one criticism of the thermal emission hypothesis, namely that the emitting areas are too small. Of course, other luminosity sources, including accretion and a shock from a rotation-powered pulsar (Campana et al. 1998a), may also occur along with thermal emission. An important
Accretion pushes a given fluid element in the crust ever deeper and forces the electron Fermi energy to grow with time. The electrons eventually capture onto nuclei (Haensel & Zdunik 1990), which become progressively neutron rich and then fuse via pycnonuclear reactions. This heat is locally deposited in the crust about the thin layers in which the reactions occur. Most of the heat is conducted into the core for a steadily accreting cool NS. The interior heats up, on a timescale of \( \sim 10^5-10^7 \) yr, until either the entire crust is nearly isothermal or, if the accretion rate is sufficiently rapid, until neutrino cooling balances the heating (Miralda-Escude et al. 1990; Brown & Bildsten 1998).

The situation is different for a transiently accreting NS. During an outburst, the reactions locally heat the crust at a rate \( Q_{\text{nuc}} \) and raise its temperature by \( \sim 1\% \). The layer in which the reactions occur (shaded region, Fig. 1) is then hotter than both the atmosphere and the core. After the rapid accretion stops, the crust cools and its thermal profile relaxes to that of an isolated cooling NS, i.e., the temperature monotonically increases with depth. While the crust heats and cools in response to the changing accretion rate, a fraction \( f \) of the deposited heat flows inward and adds to the heat stored in the core, while a fraction \( (1 - f) \) flows outward and radiates away. By equating the sum of the quiescent luminosity from the cooling core (we use the core temperature-luminosity relation for an atmosphere with an accreted mass of \( 3 \times 10^{-11} M_\odot \), Potekhin, Chabrier, & Yakovlev 1997) and the neutrino luminosity (modified Urca; Friman, & Maxwell 1979; crust neutrino bremsstrahlung; Pethick & Thorsson 1997) with the energy deposited during the outburst, we determine \( T_c \). For example, using the core temperature-luminosity relation for a fully accreted envelope (Potekhin et al. 1997) implies \( T_c \approx 10^4(f/M/10^{-11}M_\odot\text{ yr}^{-1})^{0.4} \) K. For these temperatures, neutrino cooling is unimportant.

After many outbursts, the core reaches an equilibrium limit cycle, in which the heat it loses between outbursts (the incandescent luminosity \( L_i \)) is replenished by the fraction \( f \) of the nuclear energy deposited during each outburst. We expect that all observed transient NSs will have long since reached this equilibrium limit cycle. The timescale to heat the core is much shorter than the lifetime of a low-mass X-ray binary; at \( \langle M \rangle = 10^{-11} M_\odot \text{ yr}^{-1} \), the time to heat the core to equilibrium is less than \( 10^7 \) yr for \( f \approx 0.01 \). Since the energy injected into the crust during the outburst period \( t_o \) is absorbed during the recurrence interval \( t_r \), we expect an average incandescent luminosity

\[
L_i \approx f Q_{\text{nuc}} \left( \frac{1}{t_o} \int_{\text{outburst}} \dot{M} dt \right) = f Q_{\text{nuc}} \langle \dot{M} \rangle. \tag{1}
\]

This relation, although simple, is not useful observationally because both sides of the equation depend on the source distance. To divide out this dependence, we rewrite equation (1) in terms of fluences. The outburst fluence is \( L_{o}t_o = t_o\langle \dot{M} \rangle GM/R \), and the incandescent fluence is \( L_i t_r \). The ratio of the fluences is then simply

\[
\frac{L_i t_r}{L_{o}t_o} = \frac{GM/R}{f Q_{\text{nuc}}} \approx \frac{200}{f}. \tag{2}
\]

Because the core temperature cannot appreciably change in a single outburst, there will be little change in the incandescent luminosity from one outburst cycle to the next.

While the crust relaxes to a cooling thermal profile and radiates the fraction \( 1 - f \) of the deposited energy, the neutron star luminosity asymptotically approaches \( L_i \) on the thermal diffusion timescale (Henyey & L'Ecuyer 1969),

\[
t_{\text{th}} \approx \frac{1}{4} \left( \int_{0}^{P} \left( \frac{c_p}{\rho K} \right)^{1/2} \frac{dP}{g} \right)^{2} \approx 1 \text{ yr} \left( \frac{2 \times 10^{14} \text{ cm} \text{ s}^{-2}}{g} \right)^{1/2} \left( \frac{P}{10^{31} \text{ ergs cm}^{-3}} \right)^{3/4}. \tag{3}
\]

Here \( P \) is the pressure, \( g \) is the surface gravity, \( c_p \) is the specific heat, and \( K \) is the conductivity (see Brown & Bildsten 1998 for details). In Figure 1, we plot \( t_{\text{th}} \) as a function of pressure for a NS accreting at \( \langle \dot{M} \rangle = 10^{-11} M_\odot \text{ yr}^{-1} \). The thermal diffusion time in the crust is insensitive to the temperature and hence is almost independent of accretion rate.

For objects with lower outburst fluences (e.g., Aql X-1, for which \( t_o \approx 1 \) yr and \( t_r \approx 30 \) days), most of the heat is stored in the core, i.e., \( f \approx 1 \). The reason is that the energy deposited in the outburst only raises the crust temperature by \( \sim 0.1(M/10^{-11} M_\odot \text{ yr}^{-1}) (t_o/1 \text{ yr}) \% \). As a result, the luminosity radiated as the crust relaxes is only \( \sim 0.3\% \) different from the incandescent luminosity. Note that this argument does not hold for objects with similar \( \dot{M} \) but longer recurrence times, such as Cen X-4 and 4U 1608-52. For these objects, the crust temperature can change by \( \sim 10\% \) during an outburst, and so we expect \( f < 1 \).

Figure 2 displays \( L_i/L_{o} (L_n \) is the observed quiescent luminosity) as a function of \( t_{\text{th}}t_o \) for some NSs (filled squares) and black hole (BH) (open squares) transients. Note that the BH candidates appear uncorrelated compared to the NSs. We also plot the relation for \( L_i \) (eq. [2]) for different values of \( f \). EXO 0748–676 has \( L_{o}t_o \approx 1000 \) and from the diagram appears likely to accrete during quiescence. Indeed, it is presently

\[
\frac{L_{o}t_o}{f Q_{\text{nuc}}} \approx 200, f \approx 0.01.
\]
accreting (as indicated by the RXTE/All-Sky Monitor) at an even higher rate ($L \sim 10^{40}$ erg s$^{-1}$) than when the $L_q$ for Figure 2 was measured. Repeated observations after the NS goes into quiescence can discern the fraction of the heat radiated as the crust relaxes, i.e., $1 - f$. The sum of this fluence and the incandescent fluence is just $Q_{inc}(M_{\odot})$. These observations can in principle constrain $g$, on which the thermal time strongly depends (eq. [3]).

3. THE REPERCUSSIONS OF DEEP HEATING

3.1. Observational Signatures

The expected heating in the crust naturally generates an incandescent luminosity $L_q$ that matches the observed values of $L_q$. Of course, the star may still accrete, either persistently or spasmodically, in quiescence (Narayan, Garcia, & McClintock 1997). Accretion onto the NS surface at low rates will also produce a thermal spectrum (Zampieri et al. 1995), so a further challenge is to distinguish between the two luminosity sources. If the NS does not accrete during quiescence, there will be (1) little variation in $L_q$ from one outburst cycle to the next (we here mean the incandescent luminosity emitted after the crust has relaxed to a cooling thermal configuration), (2) a slow monotonic decrease in flux and $T_{\text{eff}}$ while the crust relaxes after the outburst, (3) no short-term intensity fluctuations (barring environmental effects), (4) stability of the ratio of the NS radius to distance (as inferred from spectral fitting), and (5) an absence of metals in the spectra.

The quiescent energy spectra of 1608–52, Cen X-4 (both observed with ASCA; Asai et al. 1996b), and Aql X-1 (observed with ROSAT/Position Sensitive Proportional Counter; Verbunt et al. 1994), when fit by a blackbody (BB) with an additional power-law tail for Cen X-4, imply substantially smaller radii (1.5 km for 1608–52, 1.8 km for Cen X-4, and 1 km for Aql X-1) than expected from a NS for the best-fit BB temperatures (0.16–0.30 keV). These measured radii have puzzled observers and motivated the interpretation that either the quiescent NS luminosity does not originate from the surface or only some small fraction of the surface radiates. However, the emergent spectra at $T_{\text{eff}} \lesssim 5 \times 10^6$ K is very different from a BB. The opacity is free-free dominated and is therefore proportional to $\nu^{-3}$, where $\nu$ is the photon frequency. As a result, higher energy photons escape from greater depths, where $\nu > T_{\text{eff}}$ (Romani 1987; Zampieri et al. 1995). Spectral fits of the Wien tail with BB curves then overestimate $T_{\text{eff}}$ and underestimate the emitting area, by as much as orders of magnitude (Rajagopal & Romani 1996; Zavlin et al. 1996). Simple comparisons between the observed spectra and the hydrogen atmosphere models imply larger emitting areas in all cases.

An incandescent NS should have a pure H atmosphere because the time for heavy elements to settle out of the photosphere is $\sim 10$ s (Romani 1987). However, if accretion continues in quiescence, there is an accretion rate, $M_{\odot}$, above which metals are dumped into the atmosphere fast enough to maintain their abundance. In this case a measurable metal abundance may exist. In the absence of spallation (which depends on the accretion geometry), metals will be underabundant relative to their infalling value for $M < M_{\odot} \approx 4 \times 10^{-14} M_{\odot}$ yr$^{-1}$ ($k_B T_{\text{eff}}/0.1$ keV)$^{1/2}$ (Bildsten, Salpeter, & Wasserman 1992). The accretion rate $M_{\odot}$ coincides with the accretion rate at which the resulting luminosity from quiescent accretion, $G M M_{\odot}$, is comparable to the thermal emission. If accretion alters the luminosity, it also alters the photospheric abundances. The emergent spectra from an atmosphere with solar abundance metals is detectably different from that of a pure H atmosphere (Rajagopal & Romani 1996), mostly because of the gravitationally redshifted O VIII photoionization edge. This feature (at 0.87 keV in the rest frame of the ion), if detectable with XMM, would allow direct measurement of the gravitational redshift.

Thermal emission does not explain the hard power-law tail seen in both Cen X-4 (Asai et al. 1996b) and Aql X-1 (Campana et al. 1998b), Evidence of an additional luminosity source is also indicated by the fast (timescales of order days) variations in the quiescent flux observed from Cen X-4 (Campana et al. 1997). If a rotation-powered pulsar becomes operational in quiescence, the pulsar wind can interact with material in the NS environment, similar to that in pulsar/B e star system PSR 1259–63 (Tavani & Arons 1997). The emission from the shock is most likely nonthermal, however, so future observations can distinguish the part of the spectrum contributed by thermal emission.

3.2. Aql X-1 and SAX J1808.4–3658

Recent observations of Aql X-1 as it faded into quiescence (Campana et al. 1998b; Zhang, Yu, & Zhang 1998a) revealed an abrupt (1 day) decay of the luminosity following a more gradual decline with a roughly 17 day timescale. After the sudden dimming, the luminosity persisted at $L_q \sim 10^{33}$ ergs s$^{-1}$ for the remainder of the observation. Both Campana et al. (1998b) and Zhang et al. (1999b) interpreted this sharp transition as the onset of the propeller effect (centrifugal barrier). Accretion at the low rates ($\approx 10^{-13} M_{\odot}$ yr$^{-1}$) needed to explain
$L_\nu$ is very difficult if the propeller is operational (Stella et al. 1994). In addition, accretion in spite of the propeller implies a flow onto the polar caps that would produce luminosity variations at the NS spin period, which are not seen. The propeller can be avoided only if the NSs in Aql X-1 rotate with $P > 0.6(B/10^9 G)^{0.67}$ s (Verbunt et al. 1994). Interpreting the 549 Hz oscillation seen during a type I burst from Aql X-1 (Zhang et al. 1998a) as the rotational frequency would then imply that $B < 10^4$ G. This magnetic field constraint relaxes substantially if thermal emission causes $L_\nu$ and makes more plausible the NS becoming an active millisecond radio pulsar.

The steadiness of $L_\nu$ (over a 20 day observation with BeppoSAX; Campana et al. 1998b) is naturally explained by thermal emission, provided that $f \approx 1$ (which we expect from the arguments in § 2). The incandescent emission from the hot NS has the correct magnitude to explain the observations without requiring any ad hoc assumptions. Alternate explanations, such as accretion onto the magnetopause or shock emission from a rotation-powered pulsar (Campana et al. 1998a), are unlikely to produce both a steady luminosity and a thermal spectrum, especially one with an emitting radius comparable to that of a NS. However, at least one other emission mechanism is required to account for the hard tail.

With the recent discovery of a 401 Hz accreting pulsar (Chakrabarty & Morgan 1998; Wijnands & van der Klis 1998) in the transient SAX J1808.4–3658 (in’t Zand et al. 1998), an upper bound of $6 \times 10^{26}$ G cm$^{-3}$ may be placed on the dipole magnetic field if the magnetospheric radius is presumed to be less than the corotation radius. Given a recurrence interval of 1.5 yr, an outburst duration of $\approx 20$ days, and an outburst accretion rate of $\approx 10^{-11}$ $M_\odot$ yr$^{-1}$ (in’t Zand et al. 1998), we expect an incandescent luminosity of $\approx 6 \times 10^{32}$ ergs s$^{-1}$ ($f/1.0$), which corresponds to an unabsorbed flux (4 kpc distance) of $3 \times 10^{13}$ ergs cm$^{-2}$ s$^{-1}$ ($f/1.0$). The inferred surface magnetic field and spin period are sufficient to power a rotation-powered pulsar. If this occurs, the magnetospheric emission is $L_\nu \approx 4 \times 10^{32}$ ergs s$^{-1}$ (Becker & Trümper 1997) and may contaminate the thermal emission.

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4. CONCLUSIONS

We have demonstrated that reactions in the inner crust of an accreting NS heat the interior enough to make the NS incandescent after accretion halts. Transiently accreting NSs then radiate $\approx 5 \times 10^{32} - 5 \times 10^{33}$ ergs s$^{-1}$ in quiescence. The quiescent emission is a thermometer that probes the heated deep crust and core. As in the case of isolated cooling NSs (see, e.g., Tsuruta 1998), it may be possible to test for the presence of enhanced neutrino emissivities by placing limits on the interior temperature of the NS.

Upcoming missions will greatly increase our understanding of previously discovered transients and open up new populations for study. Especially promising are the low-luminosity X-ray sources in globular clusters (Hertz & Grindlay 1983). A subject of debate is whether the brighter sources of this class (with $10^{33}$ ergs s$^{-1} < L < 10^{34.5}$ ergs s$^{-1}$) are quiescent soft X-ray transients, as opposed to cataclysmic variables (Verbunt, van Paradijs, & Elson 1984). If so, future X-ray observations may mine a potentially rich source of NS transients. With multiple quiescent NSs in a single field of view, all at the same distance and reddening, comparisons between sources will be easier and radius determinations more certain. Although in many ways distinct from the low-mass systems, the neutron stars in Be transients (Apparao 1994; van den Heuvel & Rapport 1987) should also behave as we have discussed. These NSs have strong magnetic fields ($B \approx 10^{14}$ G), show pulsations, and undergo a variety of outbursts (Bildsten et al. 1997).

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