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Electron Capture Reactions in Neutron Star Crusts: Deep Heating and Observational Constraints

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We compute the nucleosynthesis in the outer crust of an accreting neutron star, starting with an rp-process distribution of nuclei and integrating to neutron-drip density. Our reaction network includes temperature-dependent continuum electron capture rates and realistic sources of heat loss by thermal neutrino emission from the crust and core. We show that, in contrast to previous calculations, electron captures into excited states and subsequent γ-emission significantly increases the local heat deposited into the outer crust. This heating raises the crust temperature and reduces the critical accreted mass needed for unstable ignition of $^{12}\mathrm{C}+{}^{12}\mathrm{C}$, which is thought to trigger superbursts observed from some accreting neutron stars. As a result, the superburst recurrence time is shortened, which brings calculations of the superburst ignition depth closer to that inferred from observations.

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1. Introduction

Neutron stars are an excellent natural laboratory for studying the physics of dense matter. In recent years, the ability to monitor the X-ray sky with instruments such as *RXTE* and *BeppoSAX* has opened up new vistas into the interior physics of the neutron star from observations of transient phenomena. An excellent example are superbursts [for a review, see 1] Like normal type I X-ray bursts (XRBs), superbursts are characterized by a rapid rise in the lightcurve followed by a cooling tail; unlike type I X-ray bursts, superbursts are roughly $\sim 10^3$ times more energetic, have cooling timescales of hours instead of seconds, and recur on timescales of years instead of hours. The currently favored scenario for these superbursts is thermally unstable ignition of $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ at densities $\sim 10^8 - 10^9\,\mathrm{g\,cm^{-3}}$ [2, 3]. The cooling superburst lightcurve follows a broken power-law [4], with the location of the break in slope dependent on the ignition depth. This ignition depth is sensitive to the temperature in the neutron star crust. As a result, observations of superbursts can inform us about the neutrino emissivity of the neutron star crust and core [5, 6, 7].

In addition, there are now several *quasi-persistent transients* known. These are neutron stars that accrete intermittently from a companion star, with accretion outbursts lasting for years–decades, followed by long quiescent intervals in which the accretion rate is very small or zero. When the source goes into quiescence, the crust thermally relaxes. Recent observations of KS 1731$-$260 and MXB 1659$-$29 [8] have followed this thermal relaxation and find that the decay is best fit by an exponential decay to a constant value. This has exciting implications for measuring the heat capacity and thermal conductivity of the crust and the neutrino emissivity of the core.

Both of these phenomena are controlled by the temperature in the deep crust of the neutron star, which is determined by balancing heat deposited from reactions with radiative cooling from the surface and neutrino emission from the crust and core. A fluid element in the crust is compressed by the continual accretion of matter onto the neutron star surface. As a result, the pressure and electron chemical potential μ_e of a given fluid element steadily increase with time. Over the mass-transfer lifetime of the binary, enough matter can be transferred to replace the entire crust, and the composition of the crust is therefore set by the resulting electron captures, neutron emissions, and pycnonuclear reactions [9, 10, 11] that deposit into the crust ~ 1.5 MeV per accreted nucleon.

Previous studies of these crustal reactions used a single representative isotope, e.g, ^{26}Fe or ^{106}Pd, for the ashes of H/He burning. The electron captures occur in two stages[10]. The first is at near-threshold onto an even-even nucleus ($(Z,A)+e^- \rightarrow (Z-1,A)+\bar{\nu}_e$, where Z and A are even). Because of the odd-even staggering of the nuclear masses the electron capture threshold E_thr for the odd-odd nucleus $(Z-1,A)$ is lower than on (Z,A). Consequently, following the first capture, the electron energy E_e is well above threshold $E_\mathrm{thr}^{Z-1\rightarrow Z-2}$ and a second capture $(Z-1,A)+e^- \rightarrow (Z-2,A)+\bar{\nu}_e$ immediately follows. In general, the heat deposited in the crust for a transition is $\approx E_\mathrm{exc}+(E_\mathrm{e}-E_\mathrm{thr})/4$, where E_exc is the excitation energy of the state into which the electron is captured, and the factor 1/4 arises from the phase-space integration in the limit $(E_\mathrm{e}-E_\mathrm{thr})/E_\mathrm{e} \ll 1$.

Where experimental data were lacking, which is the case for the vast majority of nuclei, [10, 11] estimated the heat deposited into the crust by setting $E_\mathrm{exc} \rightarrow 0$. As a result, in their calculation, electron captures in the outer crust contributed little heat to the neutron star crust, and the crust temperature was set by processes in the inner crust (where free neutrons are present, at densities $\rho \gtrsim 4\times 10^{11}\,\mathrm{g\,cm^{-3}}$). Here we report on network calculations of the evolution of an accreted fluid element being compressed by continual accretion in the outer crust. We find that the heat deposited in the outer crust is substantially greater than previous estimates; this heating lowers the amount of mass needed to trigger a superburst.

2. Heat Sources in the Outer Crust

The evolution of the composition and the associated nuclear energy generation is calculated with a nuclear reaction network of 1430 isotopes spanning nuclei from proton-rich rp-process ashes to the neutron dripline, in the mass range $A = 1$–106. Temperature and density-dependent electron capture and β-decay rates have been calculated in the quasi–particle random-phase approximation (QRPA) [12]. The single–particle level structure is computed from a folded–Yukawa potential. Ground-state deformation parameters and masses were obtained from the Finite-Range Droplet Model [13]. Pairing is treated using the Lipkin–Nogami method. Only allowed Gamov-Teller transition rates are considered and neutrino losses are accurately calculated for each transition. As temperatures are low and radiative deexcitation timescales are much faster than weak interation timescales, we assume that the parent nuclei are in their ground states. We use a new analytic phase space approximation (Gupta, in preparation) that is valid for low temperatures for computing the electron capture rates. In addition, our network includes neutron capture rates calculated with the statistical Hauser-Feshbach model NON-SMOKER [14]. The corresponding (γ,n) rates are calculated from detailed balance.

We integrate the reaction network following a fluid element as it is compressed from a density $6.0\times10^{6}\,\mathrm{g\,cm^{-3}}$ with a composition set by rp-process burning of H/He [15]. We set the temperature at this density to 4×10^{8} K, and assume steady spherical accretion at $3.0\times10^{17}\,\mathrm{g\,s^{-1}}$ (typical of superbursting sources). Our integration continues until the neutron abundance begins to rise steeply ($\mu_{\mathrm{e}} \gtrsim 20$ MeV; $\rho \gtrsim 2\times10^{11}\,\mathrm{g\,cm^{-3}}$). The resulting heat deposition and isotopic abundances are then used to construct a new thermal profile, following the methods described in [16, 5]. We use a neutron star mass 1.6 $M_{\odot}$ and radius 10.8 km, and set the crust-core boundary to be at $\rho = 1.6\times10^{14}\,\mathrm{g\,cm^{-3}}$. We assume that the core neutrino emissivity is dominated by modified Urca, and in the inner crust we use the composition and heating from [10]. Using this new $\{T(r),\rho(r)\}$ profile, and we then repeat the network integration to obtain a new composition and and heat deposition, and continue iterating until the temperature and composition has converged—typically within a few iterations. Fig. 1 shows the integrated deposited energy Q (*solid line*) as a function of μ_{e}. We find, that in the crust where $\mu_{\mathrm{e}} \lesssim 14$ MeV ($\rho \lesssim 6\times10^{10}\,\mathrm{g\,cm^{-3}}$) electron captures deposit $\approx 70\ \mathrm{keV\,u^{-1}}$, which considerably exceeds the previous estimate of $\approx 20\ \mathrm{keV\,u^{-1}}$ [11] (*dashed line*).

To understand these results, we construct the following approximation. For each A, we trace the heat deposition from successive electron captures, starting from a single isotope (Z,A) that is stable at low densities, and then increasing μ_{e} up to 20 MeV. We neglect (γ,n) and (n,γ) reactions. For each nucleus, we identify the lowest excited state with significant Gamow-Teller strength and assume that the electron captures into it. We then write the heat deposited by each capture as $(E_{\mathrm{e}} - E_{\mathrm{thr}} - E_{\mathrm{exc}})/4 + E_{\mathrm{exc}}$. The total heat deposited per nucleon for each mass chain A is shown in Fig. 1 (*right panel*). For comparison the two stars at $A = 56$ and $A = 106$ show the previous estimates [10, 11]. It is evident from this plot that the heat deposited in the outer crust dramatically varies with composition. Using this estimate of the heat deposited by each transition, we then weight the heat deposited by each A with its abundance in the rp-process ashes to obtain the heat deposition as a function of μ_e (Fig. 1, *dotted line*). It reproduces the network calculation amazingly well until $\mu_e \gtrsim 14$ MeV, where (γ, n) and (n, γ) reactions begin to reshuffle the abundances of the different isobars.

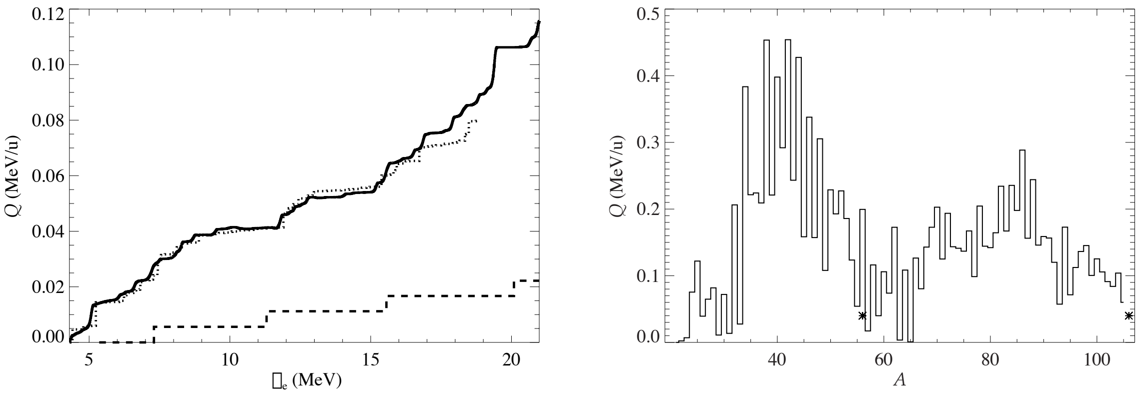

Figure 1: ***Left*** Integrated heat release in the crust from the compression of rp-process ashes (*solid line*). For comparison, the integrated heat released in the model [11] is also shown (*dashed line*), as is the result from our simple model (*dotted line*). ***Right*** Total heat released for single mass chains with $A = 20$–105 over the interval $\mu_e < 20$ MeV. The asterisks indicate the values from [10, 11].

3. Discussion

What are the implications of this enhanced heating in the outer crust, and are there any observable signatures of this heating? Here we mention one phenomena for which it makes a difference: the critical accreted mass needed to ignite superbursts. As noted by [7], models of neutron star crusts with a strong crust neutrino emissivity from $^1S_0$ pairing of superfluid neutrons (but see [17]) where $k_B T \sim \Delta$, the gap energy, systematically predict a much larger superburst ignition mass than inferred from observations. The additional heating in the outer crust partially alleviates this discrepancy. The increased heat deposited in the crust elevates the temperature and reduces the depth, and hence the recurrence time, of unstable ^{12}C ignition by as much as a factor of 3. We shall discuss our crust models, and their implications, in more detail in a forthcoming publication (Gupta et al., in preparation).

References

[1] E. Kuulkers, *The Observers' View of (very) Long X-ray Bursts: They Are Super!*, in *The Restless High-Energy Universe* (E. van den Heuvel, J. in 't Zand, and R. Wijers, eds.), Nucl. Phys. B Suppl Series, Elsevier, 2003. `astro-ph/0310402`.

[2] A. Cumming and L. Bildsten, *Carbon Flashes in the Heavy Element Ocean on Accreting Neutron Stars*, *ApJ* **559** (2001) L127, [`astro-ph/0107213`].

[3] T. E. Strohmayer and E. F. Brown, *A Remarkable Three Hour Thermonuclear Burst from 4U 1820-30*, *ApJ* **566** (2002) 1045, [astro-ph/0108420].

[4] A. Cumming and J. Macbeth, *The Thermal Evolution following a Superburst on an Accreting Neutron Star*, *ApJ* **603** (2004) L37–L40, [astro-ph/0401317].

[5] E. F. Brown, *Superburst Ignition and Implications for Neutron Star Interiors*, *ApJ* **614** (2004) L57, [astro-ph/0409032].

[6] R. L. Cooper and R. Narayan, *Theoretical Models of Superbursts on Accreting Neutron Stars*, *ApJ* **629** (2005) 422–437, [astro-ph/0410462].

[7] A. Cumming, J. Macbeth, J. J. M. in't Zand, and D. Page, *Long Type I X-ray Bursts and Neutron Star Interior Physics*, *ApJ* **646** (2006) 429, [astro-ph/0508432].

[8] E. M. Cackett, R. Wijnands, M. Linares, J. M. Miller, J. Homan, and W. H. G. Lewin, *Cooling of the Quasi-Persistent Neutron Star X-ray Transients KS1731-260 and MXB 1659-29*, *MNRAS* **submitted** (2006) [astro-ph/0605490].

[9] K. Sato, *Nuclear Compositions in the Inner Crust of Neutron Stars*, *Prog. Theor. Physics* **62** (1979), no. 4 957.

[10] P. Haensel and J. L. Zdunik, *Non-equilibrium Processes in the Crust of an Accreting Neutron Star*, *A&A* **227** (1990) 431–436.

[11] P. Haensel and J. L. Zdunik, *Nuclear Composition and Heating in Accreting Neutron-Star Crusts*, *A&A* **404** (2003) L33–L36, [astro-ph/0305220].

[12] P. Möller and J. Randrup, *New Developments in the Calculation of β-strength Functions*, *Nucl. Phys. A* **514** (1990), no. 1 1.

[13] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, *Nuclear Ground-State Masses and Deformations*, *At. Data Nucl. Data Tables* **59** (1995) 185.

[14] T. Rauscher and F. Thielemann, *Astrophysical Reaction Rates From Statistical Model Calculations*, *At. Data Nucl. Data Tables* **75** (2000) 1, [astro-ph/0004059].

[15] H. Schatz, A. Aprahamian, V. Barnard, L. Bildsten, A. Cumming, M. Ouellette, T. Rauscher, F.-K. Thielemann, and M. Wiescher, *The Endpoint of the Rp Process on Accreting Neutron Stars*, *Phys. Rev. Lett.* **86** (2001), no. 16 3471, [astro-ph/0102418].

[16] E. F. Brown, *Nuclear heating and melted layers in the inner crust of an accreting neutron star*, *ApJ* **531** (2000) 988, [astro-ph/9910215].

[17] L. B. Leinson and A. Perez, *Vector Current Conservation and Neutrino Emission from Singlet-Paired Baryons in Neutron Stars*, *Phys. Lett. B* **638** (2006) 114, [astro-ph/0606651].