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NUCLEAR PHYSICS PROBLEMS FOR ACCRETING NEUTRON STARS

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ABSTRACT

The importance of $p(e^- \nu)n$ and of (p,γ) reactions on ^{56}Ni during a thermonuclear runaway on a neutron star surface is pointed out. A fast 16-isotope approximate nuclear reaction network is developed that is suitable for use in hydrodynamic calculations of such events.

INTRODUCTION

The most popular current model for x-ray bursts involves a thermonuclear runaway in the hydrogen and/or helium layers of material accreted onto the surface of a neutron star.[1,2,3] A similar mechanism has been proposed for gamma-ray bursts.[4,5] Many hydrodynamic calculations have been based largely on an approximation network devised by Wallace and Woosley[6] (hereafter WW) which includes CNO cycle hydrogen burning (allowing for β-limitation), and a series of (p,γ) and (α,p) reactions between ^{14,15}O and ^{56}Ni. Since ^{56}Ni is a pure e^- capture nucleus, ($t_{1/2} = 6^d.1$) and has a very small $Q_{p\gamma}$ value (hence ^{56}Ni$(p,\gamma)^{57}$Cu suffers from photodisintegration), the nuclear flow generally stops at ^{56}Ni in most astrophysical situations. However, under the extreme conditions found in some neutron star accretion models, some flow may occasionally continue beyond ^{56}Ni. WW found some neutron star models to produce non-negligible amounts of ^{64}Ge and traces of elements to Y. Taam (1981, private communication) and Woosley[5] have produced flashes with temperatures above 10^9 K when the only materials left over were ^{56}Ni and ^{1}H. Under such extreme conditions, (p,γ) reactions on ^{56}Ni and higher masses can produce significant energy.

A suggestive model by Woosley[5] for rapidly (~minutes) recurring x-ray bursts depends upon ^{12}C + 2p reactions occuring when a convective instability mixes hydrogen left over from a burst into a region containing ^{12}C produced from the ^{4}He ashes of a previous burst. Such a mechanism is critically sensitive to the post-burst hydrogen abundance, which can be lowered significantly by proton captures onto heavy elements.

Calculations by Hanawa, Sugimoto, and Hashimoto[7] also suggest that (p,γ) reactions on elements heavier than Ni are important for x-ray bursts and they propose a slightly different modification of the WW approximation than that presented here. Their formalism considers masses just heavier than ^{56}Ni in detail but ignores flows beyond ^{68}Se.

Another reaction that should be included in neutron star accretion models is the weak $p(e^{-}\nu)n$ reaction. Most previous burst models assumed a neutron star surface temperature of $> 10^{8}$ K, so that hydrogen initially burned through the stable β-limited CNO cycle.[8] However, recent estimates of neutron star cooling (Hameury; 1982 private communication) suggest that many stars may have pre-accretion temperatures of 10^{6} to 10^{7} K. The hydrogen layer accreted at such cold temperatures will continue to increase in mass until its base reaches densities of $\rho > 1.4 \times 10^{7}$ g/cm^{3}, where the protons will begin to capture electrons. Such densities are also achieved in some models where unburned hydrogen remains after a thermonuclear flash, and the star continues to accrete matter onto the ashes of the previous burst.[5]

CALCULATIONS

Figure 1 shows the energy generation rate as a function of time for a solar composition ($X_H = 0.7$, $X_{He} = 0.28$, $Z = 0.02$) evolved at the constant conditions of $T = 4 \times 10^{9}$ K and $\rho = 10^{7}$

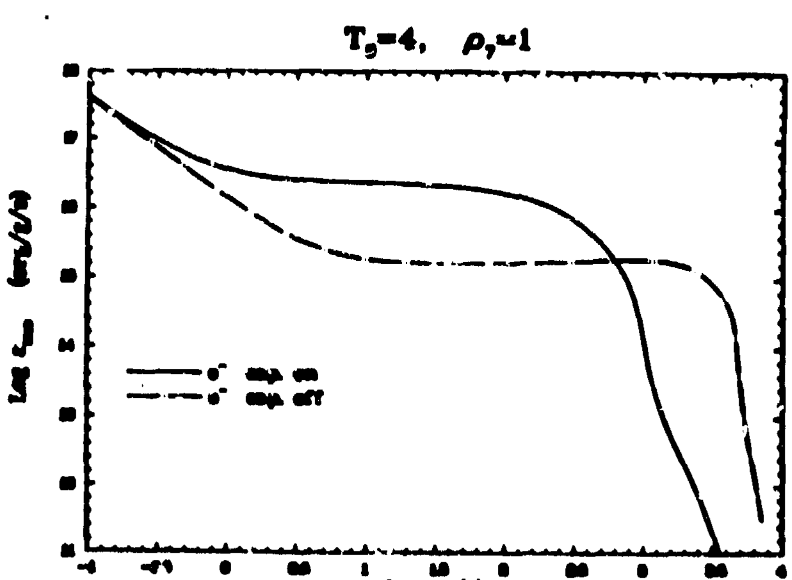


Figure 1

g/cm^3. These parameters occur in models by Woosley (1983, private communication). Note that with electron captures turned on, the hydrogen is depleted earlier, and produces an energy generation rate a factor of 15 higher than without $p(e^-\nu)n$.

To illustrate the importance of proton captures on heavy nuclei, a mixture of $X_H = 0.5$, and $X(^{56}Ni) = 0.5$ was evolved with the 250 isotope network described in WW. The density was held constant at $\rho \approx 5 \times 10^6$ g/cm^3, and the temperature was held at $T_9 = 0.5$ and 1.0. The energy generation rates are shown in Figure 2. The solid line indicates the full reaction network results, and the dashed line shows results from the approximation network described below. Note that the original approximation of WW would yield no energy, since $^{56}Ni(p,\gamma)\,^{57}Cu$ was not included there.

The revised approximation network includes equations (C1) through (C17) of WW, modified as follows: (note the typographical error in WW: (C8) should contain Λ_2, not Λ_1).

Figure 2a: $T_9 = 0.5 / \rho_6 = 5$

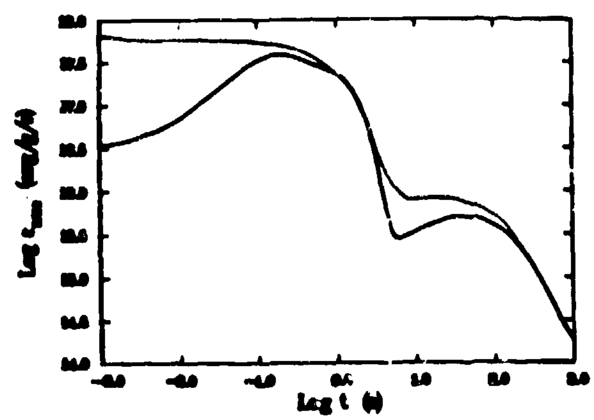
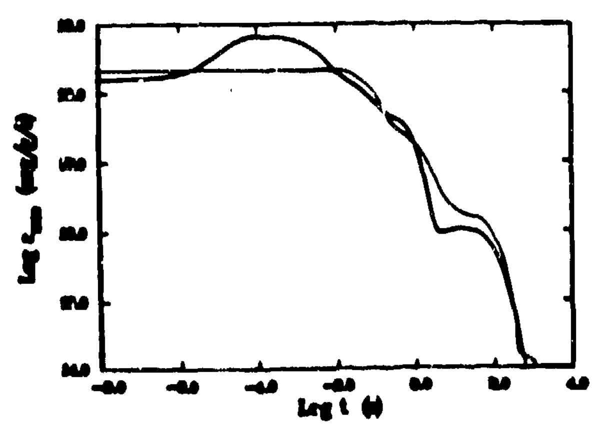


Figure 2b: $T_9 = 1.0 / \rho_6 = 5$



$$dy_{56}/dt = y_{30}\Lambda_2 - y_{56}\Lambda_3 \qquad \text{(C8)}$$

$$dy_{59}/dt = y_{56}\Lambda_3 - y_{59}\Lambda_4 \qquad \text{(C8A)}$$

$$dy_{64}/dt = y_{59}\Lambda_4 - y_{64}\Lambda_5 \qquad \text{(C8B)}$$

$$dy_{72}/dt = y_{64}\Lambda_5 - y_{72}\Lambda_6 \qquad \text{(C8C)}$$

$$dy_{80}/dt = y_{72}\Lambda_6 - y_p y_{80}\rho\lambda_{p\gamma}(^{80}Zr) \qquad \text{(C8D)}$$

$$dy_{88}/dt = y_{80}y_p\rho\lambda_{p\gamma}(^{80}Zr) - y_{88}y_p\rho\lambda_{p\gamma}(^{88}Ru) \qquad \text{(C8E)}$$

$$dy_{96}/dt = y_{88}y_p\rho\lambda_{p\gamma}(^{88}Ru) \qquad \text{(C8F)}$$

The following terms should be added to (C9) and (C10)

$$dy_\alpha/dt = \ldots -1/2\ y_p\lambda_{e^-}(p) + 1/2\ (1/2 y_p^2\rho\lambda_{pp}) \qquad \text{(C9)}$$

$$dy_p/dt = \ldots -3y_{56}\Lambda_3 - 5y_{57}\Lambda_4 - 8y_{64}\Lambda_5$$

$$-8y_{72}\Lambda_6 - 8y_p y_{80}\rho\lambda_{p\gamma}(^{80}Zr) - 8y_p y_{88}\rho\lambda_{p\gamma}(^{88}Ru) \qquad \text{(C10)}$$

$$-2y_p\lambda_{e^-}(p) - 2\ (1/2 y_p^2\rho\lambda_{pp})$$

where

$$\ell_{a_3} = y_{56}y_p\rho\lambda_{p\gamma}(^{56}Ni) \qquad (1)$$

$$\ell_{b_3} = y_{57}\ \lambda_{e^+}(^{57}Cu) \qquad (2)$$

$$\ell_{c_3} = y_{57}y_p\rho\ \lambda_{p\gamma}(^{57}Cu) \qquad (3)$$

and if $\ell_{c_3} > \ell_{b_3}$ then

$$\Lambda_3 = \min\begin{cases}\ell_{a_3}\\ \lambda_{\beta^+}(^{58}Zr) = 15.4\end{cases} \qquad (4)$$

else,

$$\Lambda_3 = \min\begin{cases}\ell_{a_3}\\ \ell_{b_3}\end{cases} \qquad (5)$$

Also,

$$\Lambda_4 = 1.05 \qquad (6)$$

$$\Lambda_5 = 0.011 \qquad (7)$$

$$\Lambda_6 = \min \begin{cases} Y_p \rho \lambda_{p\gamma}(^{72}Kr) \\ 1.2 \end{cases} \qquad (8)$$

As a very rough approximation, the equilibrium abundance of ^{57}Cu may be assumed:

$$y_{57} = 2.08 \times 10^{-10} \rho y_p y_{56} T_9^{-3/2} \exp(8.02/T9)$$

so that ^{57}Cu need not be carried in the network. The pp reaction is included as the last term in equations (C9) and (C10), since it can be important in cold material, and is easy to incorporate. The λ_{pp} rate can be found in Harris, et. al.[9]. The $\lambda_{e^-}(p)$ rate can be interpolated from Ref. 10. Other (p,γ) rates can be calculated from Eq. (30) of Woosley, et. al., although we employed $\lambda_{p\gamma}(^{56}Ni)$ from WW. The numerical values appearing in equations (6) - (8) were obtained by taking a rate $\ell = 1/[\sum \tau_m]$, where τ_m are mean decay lifetimes along a typical flow path between network nuclei.

CONCLUSIONS

The above equations represent a 16-element approximation network that includes ^1H, ^4He, ^{12}C, ^{14}O, ^{15}O, ^{16}O, ^{17}F, ^{22}Mg, ^{30}S, ^{56}Ni, ^{59}Zn, ^{64}Ge, ^{72}Kr, ^{80}Zr, ^{88}Ru, and ^{96}Cd. We have found some conditions for which the nuclear flows reach ^{96}Cd, but including higher mass isotopes does not appreciably increase the energy production or hydrogen depletion rates.

It should be noted that no nuclear data exists for very proton-rich isotopes above ^{56}Ni. Decay rates are estimated from Takahashi, et. al.[12] and mass excess predictions taken from Maripuu[13] and Moeller and Nix[14]. In particular, it is not known whether ^{65}As is proton-unbound. We have assumed it is; however, if $^{64}Ge(p,\gamma)^{65}As$ were allowed, the predicted energy generation rate would be higher, and exhibit a much different shape since the $^{64}Ge(\beta^+\nu)^{64}Ga$ rate is the slowest reaction above ^{56}Ni.

Other severe difficulties at low temperatures and high densities are the unknown electron screening correction to the strong reaction rates, and the pycronuclear rates (especially for the $3\alpha \rightarrow {}^{12}C$ reaction).

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