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MASTER

TITLE: THERMONUCLEAR RUNAWAYS IN THICK HYDROGEN-RICH ENVELOPES OF NEUTRON STARS

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THERMONUCLEAR RUNAWAYS IN THICK HYDROGEN RICH ENVELOPES OF NEUTRON STARS

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ABSTRACT

We have used a Lagrangian, fully implicit, one-dimensional hydrodynamic computer code to evolve thermonuclear runaways in the accreted hydrogen rich envelopes of 1.0 $M_\odot$ neutron stars with radii of 10 km and 20 km. Our simulations produce outbursts which last from about 750 seconds to about one week. Peak effective temperatures and luminosities were 2.6×10^7 K and 8×10^4 $L_\odot$ for the 10 km study and 5.3×10^6 K and 600 $L_\odot$ for the 20 km study. Hydrodynamic expansion on the 10 km neutron star produced a precursor lasting about 10^{-4} seconds.

INTRODUCTION

We have studied thermonuclear runaways in the accreted hydrogen rich envelopes of 10 km and 20 km neutron stars using a fully implicit, Lagrangian, hydrodynamic computer code which incorporates a nuclear reaction network[1]. We have assumed that the Bursters and Transient X-ray sources occur as a result of mass transfer from a secondary onto a neutron star in an analogous fashion to the nova phenomena[2]. Reviews of published work on this subject can be found in the literature[3,4].

The published work[3] has produced simulations of the Burster phenomena which are in reasonable agreement with the observations but have not yet reproduced the full range of observed behavior. By this we mean that observed Bursts show a very wide range of time

scales lasting from seconds to minutes and the published work has, so far, only addressed the characteristics of the shortest bursts. If one wants to prolong the time scale, then there are three possibilities all of which involve increasing the amount of fuel available for nuclear burning. First, one can assume that the luminosity of the neutron star is low and the mass accretion rate is low and build up a thick hydrogen envelope. Second, one can assume a rapid inflow of material and include the accretion energy in the radiative losses; and, third, one can assume that at some accretion rate the hydrogen will burn stably and a thick layer of helium can be built up on the neutron star.

Because of the success of the studies of Joss[3] and Taam[4] reviewed in this volume by Joss, we have concentrated on a regime of the ($\dot{M}$,L) plane not yet studied by these investigators: that of low internal neutron star luminosity and low mass accretion rates. In our case we are trying to both model the long time scale phenomena observed from some Bursters and to understand the cause of the very long time scale outbursts of the Transients.

Our computer code has previously been used in studies of the nova outburst,[5,6,1] thermonuclear runaways in the accreted hydrogen rich envelopes of white dwarfs, and is ideally suited to this

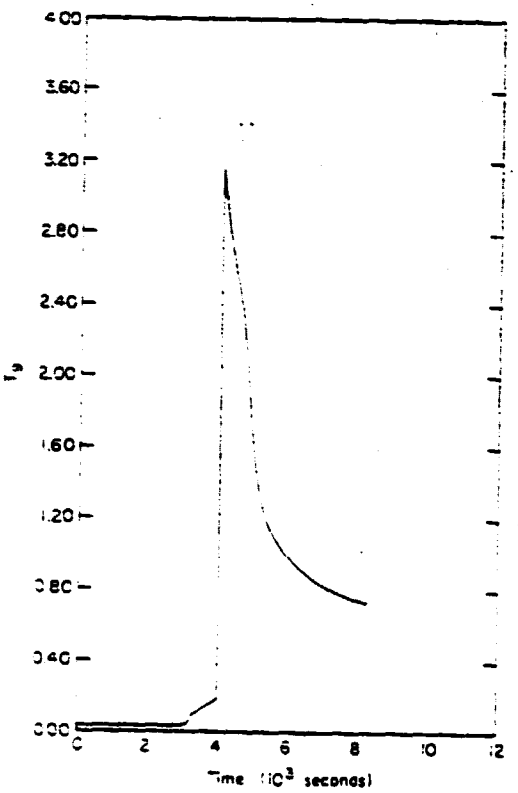

Fig. 1. The temperature as a function of time.

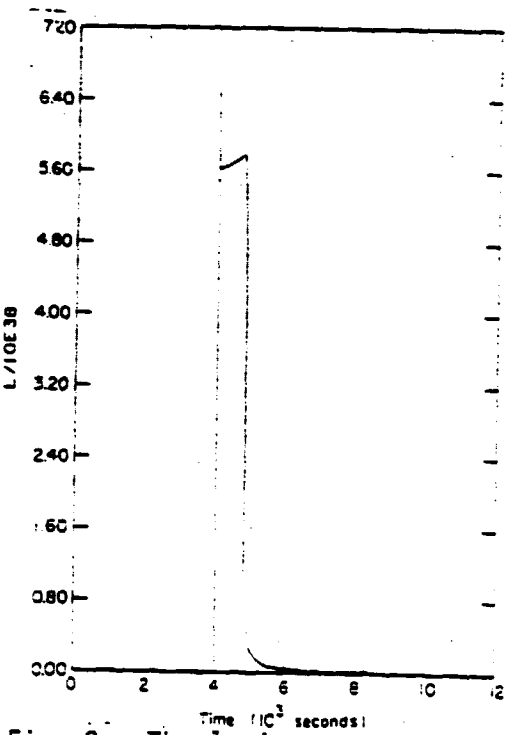

Fig. 2. The luminosity as a function of time.

study. The physics that we include is described elsewhere[7]. We include the p-p chain, the CNO reactions, the triple-α reaction, the $^{12}C(\alpha,\gamma)^{16}O$ reaction and, finally, assume that the $^{14}O(\alpha,p)^{17}F$ and $^{15}O(\alpha,\gamma)^{19}Ne$ reactions are acting in the fashion described by Wallace and Woosley[8]. We use these last two reactions to provide a measure of the rate of depletion of the CNO nuclei during the evolutionary sequences and then use this rate of depletion to calculate an energy generation assuming that a few further proton captures will occur.

RESULTS

The radius of model 1 was 10 km and it had an envelope mass of $1.5 \times 10^{-11}\ M_\odot$. This is a thick envelope for a neutron star of this mass but can be obtained for low accretion rates onto neutron stars with low internal temperatures[4]. Although some nuclear burning could have occurred in the deeper layers during the accretion process, we have neglected this and assumed a sharp composition interface. We shall refer to this boundary as the core-envelope

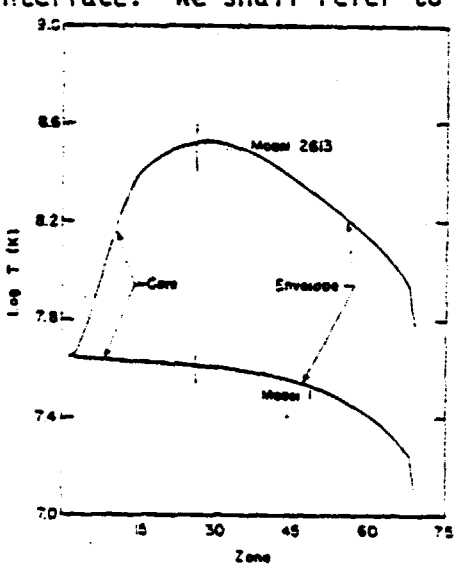

Fig. 3. The temperature as a function of mass (zone) for two times in the evolution of the 20 km neutron star.

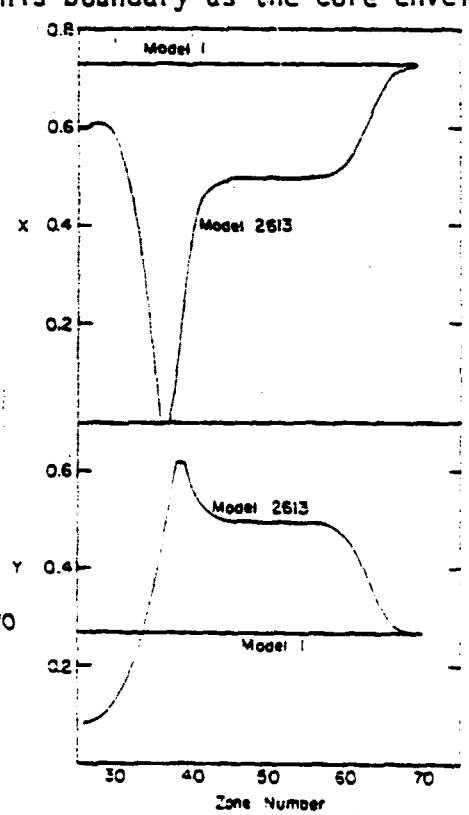

Fig. 4. The hydrogen (x) and helium (y) abundances (mass fraction) as a function of mass at two times in the evolution of the 20 km neutron star.

interface (CEI). We chose a luminosity for the neutron star of 0.1 $L_\odot$ which results in an effective temperature of 8×10^5 K. The temperature and density at the CEI are 3.3×10^7 K and 3.1×10^6 gm cm^{-3} respectively.

We begin the evolution by turning on the nuclear reactions and it takes this sequence about 760 seconds of evolution to reach a temperature of 2.45×10^9 K and an energy generation of 10^{21} erg $gm^{-1}s^{-1}$. The surface luminosity has reached 8×10^4 $L_\odot$ and the effective temperature is 2.6×10^7 K ($kT \sim 2.2$ kev). The entire envelope has become convective and is mixing fresh unburned nuclei into the shell source from the surface.

Because of our initial conditions, which may be physically realizable, the initial region of peak temperature is not at the CEI but about 10^{-12} $M_\odot$ closer to the surface. The reason for this effect is that the electron degenerate conductivity is large enough to transport the energy produced in the deepest layers of the accreted envelope into the core. This effectively keeps these

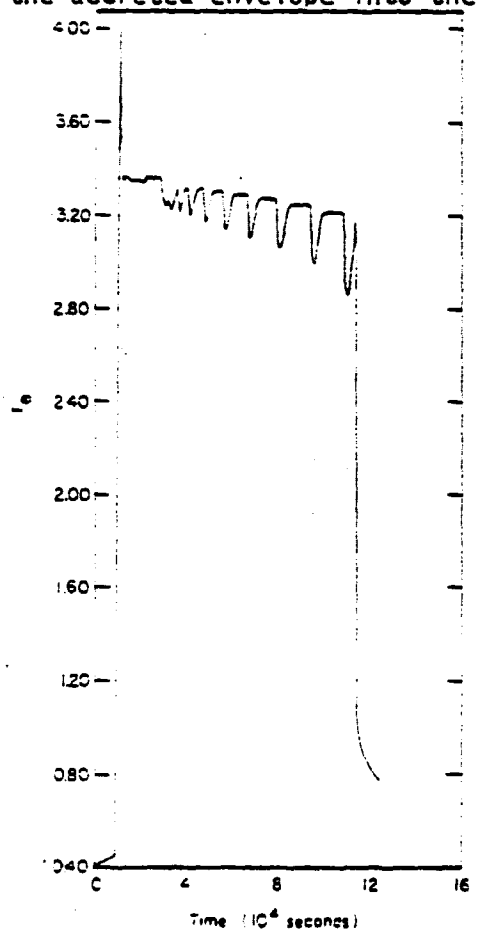

Fig. 5. The temperature at the Core-Envelope-Interface as a function of time.

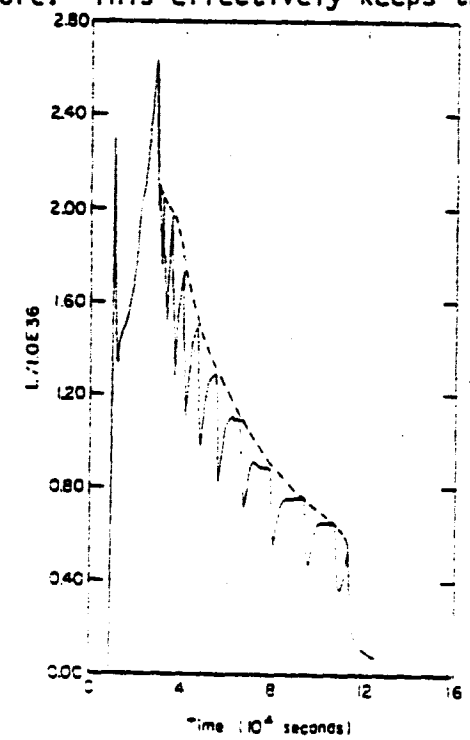

Fig. 6. The luminosity of the neutron star as a function of time.

regions cooler than the less degenerate regions closer to the surface. However, the energy produced by the shell source is now heating the hydrogen rich layers just below it and their temperature slowly climbs until they reach about 3×10^8 K. At this point they flash to a temperature of 2.8×10^9 K and an energy generation rate of 10^{25} erg $gm^{-1}s^{-1}$. This flash produces an overpressure of a few percent which results in a shock wave that reaches the surface some 5×10^{-5} sec after the flash occurred. The surface luminosity climbs to 2×10^5 $L_\odot$ and the effective temperature to 3×10^7 K. The shock causes the surface zones to expand at velocities of 2×10^3 km sec^{-1}. However, this expansion lasts for only about 10^{-6} sec and a total excursion in radius of 1.5 meters.

The shell source slowly moves inward and these layers flash to high temperatures although no more shocks occur. The temperature as a function of time for the deepest hydrogen rich shell is given in Figure 1. The hydrogen burning layers stay hot until all of the helium and most of the hydrogen is consumed. It takes about 400 seconds for this to occur and during this entire phase of nuclear burning the envelope has slowly expanded to about 12 km and remained at virtually constant luminosity. The light curve for this simulation is given in Figure 2.

Once the fuel has been burnt, the radius of the envelope slowly shrinks which maintains the high luminosity and causes a slow increase in the effective temperature of 3×10^6 K. The sequence then cools rapidly and reaches equilibrium in about an hour.

We extended our study to neutron stars with a radius of 20 km; bracketing the published work. In this case the reduced gravity should produce outbursts with lower peak luminosities and effective temperatures but the time scale for the outburst should be increased over that of the 10 km evolution. Such was the case.

For this evolution we chose an envelope mass of 2×10^{-11} $M_\odot$ which gave a temperature and density at the CEI of 4×10^7 K and 4×10^5 gm cm^{-3}, respectively. Because of the lower density, the evolution proceeds more slowly than for the 10 km case and it takes nearly 10^3 sec for the peak temperature in the envelope to reach 10^8 K. As before, this does not occur at the CEI, but a few zones closer to the surface. In addition, the lower gravity allows the envelope to expand to nearly 40 km during the evolution which prevents the temperature at the CEI from exceeding 4×10^8 K. At this temperature the $^{14}O(\alpha,p)^{17}F$ and $^{15}O(\alpha,\gamma)^{19}Ne$ reactions are removing catalytic nuclei from the CNO reaction sequence and are producing very little additional energy. This results in a most interesting phenomena. Once the shell source has reached inward to the CEI,

the temperatures are high enough for a reasonable number of α-reactions on ^{14}O and ^{15}O to occur. This is not true farther out in the envelope where the temperatures are lower. This results in the CNO reactions being able to cycle faster at lower temperatures causing an inversion in the hydrogen abundance. This can be seen in Figures 3 and 4 which show the temperatures, and hydrogen abundances at two different times in the evolution. Therefore, some 6 hours after the evolution began, the hydrogen abundance drops to zero about one-third of the way from the CEI to the surface. Because helium is nearly depleted at the CEI the α-reactions on ^{14}O and ^{15}O also become less important and the principle source of energy comes from the β^+-decays followed by proton captures. Because the CNO catalytic nuclei have their highest abundances at the edge of the region where hydrogen has become completely depleted, this is just the region where they are cycling the most rapidly and the burning front slowly moves inward and outward. However, the hydrogen abundance is low and the runaway time scale for each zone is more rapid than the time scale for the inward diffusion of heat. This allows each zone to burn out before the next inner zone can flash, producing a very ragged curve for both the temperature versus time (Figure 5) and the luminosity versus time (Figure 6). If we had been able to use more zones, these curves would have been smoother.

The peak rate of energy generation reached in this simulation was only 10^{15} erg $gm^{-1}s^{-1}$. The peak luminosity was 700 $L_\odot$ and the peak effective temperature barely exceeded 0.5 kev. It takes this sequence about one day to burn out all of the hydrogen in the shell source and for the luminosity to begin dropping. It then takes about 45 days to return to minimum. All of the hydrogen and helium are burnt to higher mass nuclei except for a thin shell of H of about 10^{-13} $M_\odot$ which is still burning but on a much longer time scale.

Because the $^{14}O(\alpha,p)^{17}F$ and $^{15}O(\alpha,\gamma)^{19}Ne$ rates are theoretical, we also investigated the effects of major changes in these rates by evolving one additional sequence with the identical initial conditions as in the previous sequence but with these rates set to zero. It takes this simulation 2×10^3 sec for the peak temperature in the envelope to reach 5×10^8 K. The rate of energy generation has reached 10^{15} erg $gm^{-1}sec^{-1}$. At this temperature a significant number of triple-α and $^{12}C(\alpha,\gamma)^{16}O$ reactions are occurring and the triple-α reaction is feeding new catalytic nuclei into the CNO cycle. This increases the value of Z and counteracts the effects of the increasing number of nuclei being trapped as ^{14}O and ^{15}O. The temperature continues to increase finally reaching 10^9K. The peak luminosity is 2.5×10^4 $L_\odot$ and peak effective temperature is 1.2 kev.

About 2×10^3 sec later, hydrogen and helium burn out and the temperature starts to drop. It takes nearly 3 days for the effective temperature to fall below 0.1 kev.

CONCLUSIONS

We have found in this study that we can produce long time scale outbursts on neutron stars if we assume low accretion rates and "cool" neutron stars. The time scales for these outbursts range from 10^3 sec for the 10 km neutron star to about one day or longer for the 20 km neutron star. The peak temperatures and luminosities were inversely proportional to the radius of the neutron stars and our calculations (plus those noted earlier) suggest that the actual radii of most neutron stars must be closer to 10 km than 20 km. On the other hand, the fast, soft, X-ray transients can be produced on larger radii neutron stars if such a wide range in neutron star radii is possible.

We also produced flat topped outbursts similar to some of those observed. Such a theoretical outburst results when the accreted envelope has had enough time to reach thermal equilibrium before the outburst begins.

Finally, we have been able to achieve outbursts in hydrogen rich material because the $^{14}O(\alpha,p)^{17}F$ and $^{15}O(\alpha,\gamma)^{19}Ne$ reactions act to remove catalytic nuclei from the CNO reaction cycle and, at high temperatures, restores the temperature dependence of the CNO reactions. In addition, at these same temperatures, the triple-α reaction is feeding new nuclei into the CN cycle which also keeps the rate of energy generation elevated over what one would predict if these reactions were not occurring.

REFERENCES

1. S. Starrfield, J.W. Truran, W.M. Sparks, Ap.J. 226, 186 (1978).
2. J.S. Gallagher, S. Starrfield, Ann. Rev. Ast. and Ap. 16, 171 (1978).
3. P.C. Joss, Ann. N.Y. Acad. Sci. 336, 479 (1980).
4. R.E. Taam, Ap.J. 241, 358 (1980).
5. G.S. Kutter, W.M. Sparks, Ap.J. 175, 407 (1972).
6. S. Starrfield, W.M. Sparks, J.W. Truran, Ap.J. Supp. 28, 247 (1974).
7. S. Starrfield, S. Kenyon, W.M. Sparks, submitted to Ap.J.(1981).
8. R.K. Wallace, S. Woosley, Ap.J. Suppl. in press (1981).