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MASTER

TITLE: HYDRODYNAMIC SIMULATIONS OF A COMBINED HYDROGEN, HELIUM THERMONUCLEAR RUNAWAY ON A 10-KM NEUTRON STAR

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HYDRODYNAMIC SIMULATIONS OF A COMBINED HYDROGEN, HELIUM THERMONUCLEAR RUNAWAY ON A 10 KM NEUTRON STAR

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ABSTRACT

We have used a Lagrangian, hydrodynamic stellar-evolution computer code to evolve a thermonuclear runaway in the accreted hydrogen rich envelope of a $1.0M_{\odot}$, 10-km neutron star. Our simulation produced an outburst which lasted about 2000 sec and peak effective temperature was 3 kev. The peak luminosity exceeded 2×10^{5} $L_{\odot}$. A shock wave caused a precursor in the light curve which lasted 10^{-5} sec.

I INTRODUCTION

The published theoretical studies of the X-ray burst phenomena have produced simulated outbursts which are in reasonable agreement with the observations (c.f., Ayasli and Joss 1982; Taam 1980). Nevertheless, there are observed bursts which occur on much longer time scales than those modeled by the above studies and, in addition, there are the transient X-ray novae which have not, as yet, been produced by any theoretical calculation. We have, therefore, made the assumption that the longer period behavior is also the result of a thermonuclear process acting in the accreted envelope of a neutron star and proceeded to study as extreme conditions on a neutron star as possible in order to try and determine the conditions necessary for such long period outbursts.

We have used a fully implicit, Lagrangian, hydrodynamic computer code to evolve a thermonuclear runaway in the accreted hydrogen rich envelope of a $1.0M_{\odot}$ neutron star with a radius of 10 km. We assume that the interior of the neutron star is cold and that the rate of accretion is low enough so that a massive envelope ($M_e \sim 10^{-11}M_{\odot}$) can be accreted before significant nuclear reactions are initiated at the boundary between the core and the accreted envelope (Starrfield, et al. 1982, hereafter SKST). We neglect nuclear reactions during the accretion process and our evolutionary sequence begins with a sharp composition discontinuity (hereafter, core-envelope interface: CEI).

Our computer code has been used in studies of thermonuclear runaways in the accreted hydrogen rich envelopes of white dwarfs in our successful attempts to simulate the nova outburst and is ideally suited to this task (c.f., Starrfield, Truran, and Sparks 1978). We have already described the physics used in this code, and our nuclear reaction network includes the p-p chain, the $^{12}C(\alpha,\gamma)^{16}O$ reaction and all relevant neutrino loss rates (Starrfield, et al. 1982). We also assume that reacting CNO nuclei are lost to the CNO reactions at rates determined by the $^{14}O(\alpha,p)^{17}F$ and $^{15}O(\alpha,\gamma)^{19}Ne$ reactions (Wallace and Woosley 1981).

II RESULTS

The initial model used in this study had a luminosity of 0.1 $L_\odot$ and an effective temperature of 8. x 10^5K. The temperature and the density at the CEI were 4.3 x 10^7K and 3.1 x 10^6 gm cm^{-3}, respectively. The initial rate of energy generation was 10^{14} erg gm^{-1} sec^{-1} producing a nuclear burning time scale in the envelope of 10^2 sec to the peak of the runaway. These conditions are certainly extreme but are not unreasonable based on our intent to simulate long period outbursts.

It takes this sequence about 130 seconds to evolve to the point where the peak temperature in the shell source reaches 10^8K. It takes about 700 seconds longer for the temperature to reach its peak value of 3.3 x 10^9K. However, because of conductive energy losses into the interior, this does not occur at the CEI but in a zone about $10^{-12} M_\odot$ closer to the surface. The rate of energy generation exceeded 10^{21} erg gm^{-1} sec^{-1} (but not for very long).

The rapid rise of the temperature in the last stages of the thermonuclear runaway causes an overpressure of a few percent in the shell source which produces a shock wave that reaches the surface 4 x 10^{-6} sec after it is initiated. When this shock penetrates the surface layers, the luminosity climbs to 2 x $10^5 L_\odot$ and the effective temperature to 3.3 x 10^7K (kT~3keV). Figure 1 shows the temperature history of the CEI, and the luminosity of the surface layers at the time of shock penetration is given in Figure 2. The 3 figures in this paper are reprinted from SKST.

Once the envelope has returned to equilibrium, a nuclear burning front moves both inward and outward from the original point of peak temperature. As it passes through each zone, it flashes to temperatures exceeding 10^9K. It takes the front about 2 sec to reach the CEI and the temperature in this zone flashes to 3 x 10^9K.

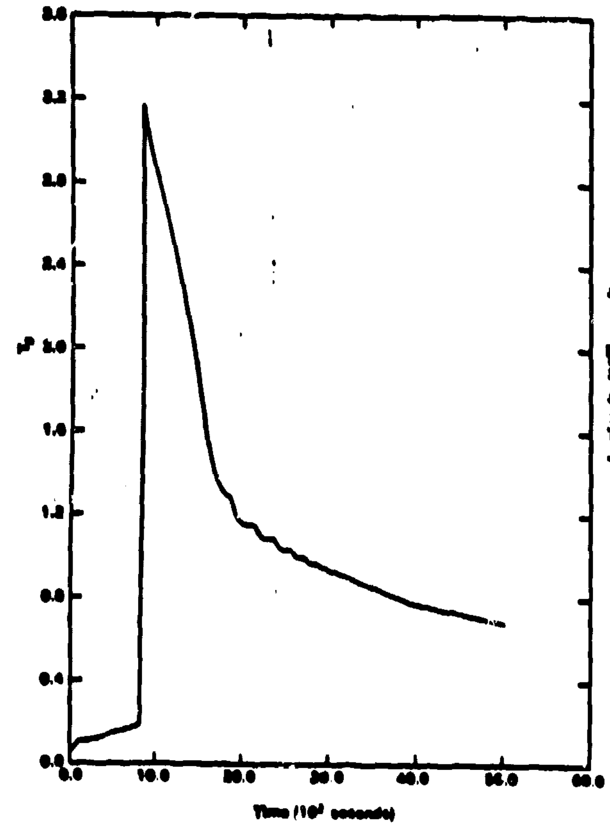

Fig. 1. The temperature of the CBI as a function of time (in units of 10^9K).

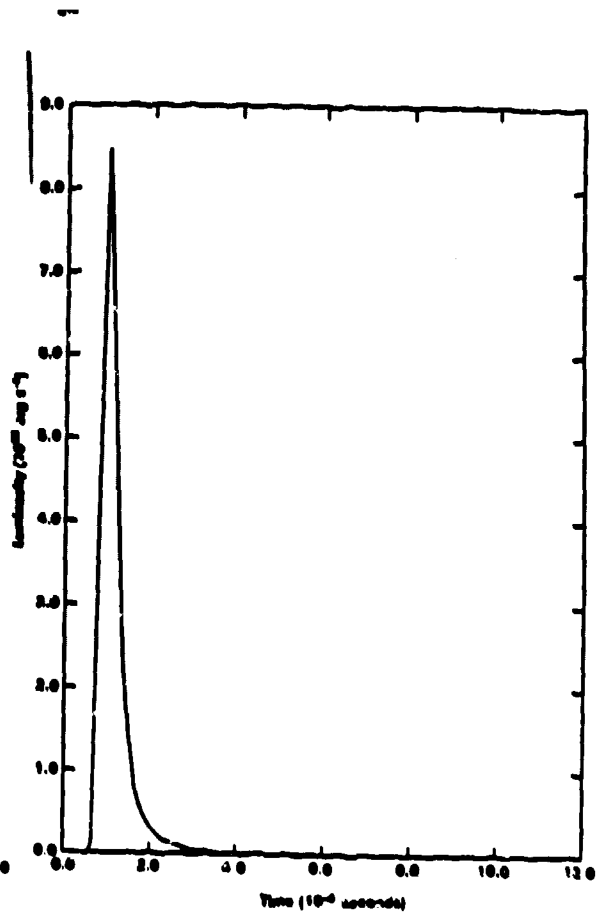

Fig. 2. The luminosity of the surface layers as a function of time when the shock wave penetrates the surface.

Up to this time the envelope has remained in hydrostatic equilibrium (except for the shock passage), but the steady heating causes the surface luminosity to reach L_{Edd} and the envelope begins to expand at a few km sec^{-1}. Shortly after it reaches a radius of 2×10^6km, the envelope becomes pulsationally unstable with the excursions in luminosity reaching factors of 2. The light curve is shown in Figure 3 where the episodes of pulsational instability appear as spikes superimposed on the steady plateau behavior.

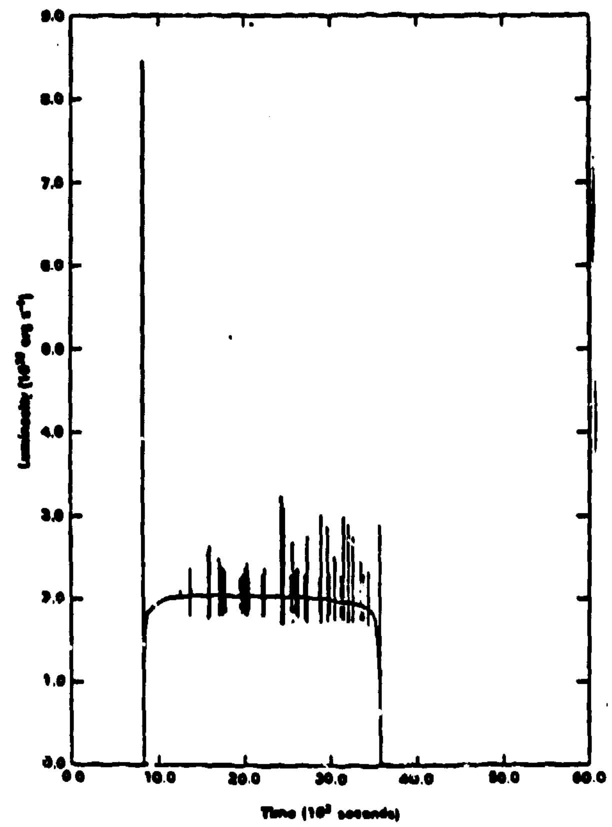

Fig. 3. The luminosity of the surface layers as a function of time during the entire outburst. The initial spike is the precursor shown in Figure 2 and the vertical bars are times of pulsational instability during the evolution.

It takes about 2000 sec of evolution for the peak temperature in the shell source (CEI) to drop to 10^9 K and the rate of energy generation in the same zone to 10^{12} erg gm^{-1} sec^{-1}. At the same time, because of the large radius, the temperature has fallen to 10^6K (kT~0.1 keV). This value is much too soft for a normal X-ray burst.

As the hydrogen fuel is consumed and the nuclear energy production declines, the envelope begins to collapse. This stage takes 10^2sec and as the radius decreases, the effective temperature climbs to 2.5×10^7K (kT ≈ 2.2keV). The energy emitted in the 2-10 keV range goes through an increase followed by a rapid decrease that would appear as a burst in a detector. Once the radius has returned to 10km, the final decline takes only 10^3sec. By 4 hours after the decline, the luminosity is 1 $L_\odot$.

III DISCUSSION

The theoretical light curve for this simulation when folded with the instrument response of a low energy X-ray detector will appear to that detector as two bursts, one with an extremely short time scale, separated by 2×10^3 sec. The peak luminosity obtained in this study, $2 \times 10^5 L_\odot$, is in close agreement with the observed values. However, the theoretical radius at maximum is certainly too large to agree with the observations (Van Paradijs 1979).

The initial conditions were chosen to represent the maximum amount of material that could be accreted by a neutron star under normal conditions. The intent was to simulate the behavior of the longer time scale outbursts. The attempt was unsuccessful and we must attribute the X-ray nova outburst to some other mechanism or combination of mechanisms. We have already proposed that the thermonuclear runaway acts as a trigger on the secondary and, in fact, causes a period of enhanced mass transfer analogous to the current hypothesis for the cause of the dwarf nova outburst.

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