THERMONUCLEAR BURNING IN THE ENVELOPE OF AN ACCRETING NEUTRON STAR

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ABSTRACT

A simple analytical method has been used to investigate thermonuclear flashes in a degenerate envelope of an accreting neutron star. The heating source is the compression of envelope and the cooling is due to the radiative cooling of the envelope. The role of hydrogen burning is discussed. A possible evolutionary scenario for formation of preburster binaries consisting of a neutron star and a low mass main sequence star is proposed.

The most promising model for explanation of bursters to date is the thermonuclear one proposed originally by Woosley and Taam (1976), Maraschi and Cavaliere (1977). A thermonuclear model has been developed in a number of papers by Joss (1977, 1978a, b) and Ergma and Tutukov (1979a) and Tutukov and Ergma (1979b).

In this paper we present results of the investigation of the thermal evolution of a shell accreted onto the surface of a neutron star.

Thermal evolution of an accreted shell strongly depends on several factors: 1) the accretion rate $\dot{M}$, 2) thermal history of the neutron star, 3) the fraction of the rest which goes into heating, 4) the chemical composition of accreted matter, 5) the opacity, and 6) the mass of the neutron star.

Let us give a brief description of our analytical method (for more details we refer to our previous papers: Tutukov and Ergma (1979) and Ergma and Tutukov (1979).

We consider a neutron star undergoing spherically symmetric accretion of the nuclear fuel from a close second component. The size of the latter and the distance between the components is of the order of or somewhat smaller than the solar radius according to the three second delay of the optical burst (Grindlay et al., 1978).

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For the flat thin envelope the condition of thermal equilibrium

$$\frac{16\pi\sigma R^2 T_{sh}^4}{3\kappa\rho_{sh}\Delta R} = \alpha c^2 \dot{M}' \qquad (1)$$

allows an estimation of the shell temperature T_{sh}. Here σ is the Boltzman constant, R is the radius of the neutron star, κ is the opacity, ρ_{sh} and ΔR are average density and thickness of the shell, c is the light velocity, and $\dot{M}'$ is the accretion rate in g/s.

α is the main parameter determining the variation of the values T and ρ. Nuclear energy gives $\alpha \approx 0.007$. The selfcompression of the shell due to the mass accumulation leads to $\alpha = GM\Delta R/R^2 = \dot{\gamma}P_{sh}/(\gamma-1)/\rho_{sh}/c^2$, where P_{sh} is the pressure at the bottom of the shell and γ is the adiabatic index. The thermal evolution of the accreting shell for $\alpha = 0.01$ was investigated in our previous paper (Ergma, Tutukov, 1979). Now we shall discuss the thermal evolution of the shell with heating due to the selfcompression only. The main equation (1) in this case transforms to:

$$T_{sh} = \begin{cases} 10^{9.64} \left(\frac{\kappa\dot{M}}{M}\right)^{1/2} \frac{\rho_{sh}^{1/2}}{\mu} & \text{for nondegenerate gas with the average molecular weight } \mu \\ 10^{7.36} \left(\frac{\kappa\dot{M}}{M}\right)^{1/4} \frac{\rho_{sh}^{7/12}}{\mu_e^{5/6}} & \text{for degenerate electron gas} \\ 10^{8.5} \left(\frac{\kappa\dot{M}}{M}\right)^{1/4} \frac{\rho_{sh}^{5/12}}{\mu_e^{2/3}} & \text{for relativistic degenerate electron gas} \end{cases}$$

$\dot{M}$ is the accretion rate in solar mass per year. The main results are given in Fig. 1 and Table 1. The ignition lines $\varepsilon_{CP} = \varepsilon_{DIF}$, $\varepsilon_{HE} = \varepsilon_{DIF}$, $\varepsilon_C = \varepsilon_{DIF}$ are shown in Fig. 1, where ε_{CP}, ε_{HE} and ε_C are the energy production rate in $C^{12}(P,\gamma)\,N^{13}$, $3\alpha \to C^{12}$ and $C^{12} + C^{12}$ reactions, respectively, and ε_{DIF} is the average radiative cooling rate (see equation (1)) of the envelope. The degeneracy border is marked by the dashed line. The dotted line marks places of stationary burning of hydrogen with $\varepsilon_{DIF} = {}^{6}10^{15}$ erg/s/g for $N_{CNO}/N_P\ 10^{-3}$, where N_{CNO} and N_P are numbers of CNO and H atoms per gram. The shell temperature in this case may be determined by

$$T_{sh} = 10^{4.14}\kappa^{1/4}\rho^{5/6}$$

If the hydrogen burning is stationary, $\alpha = 0.007$. Then equation (2)

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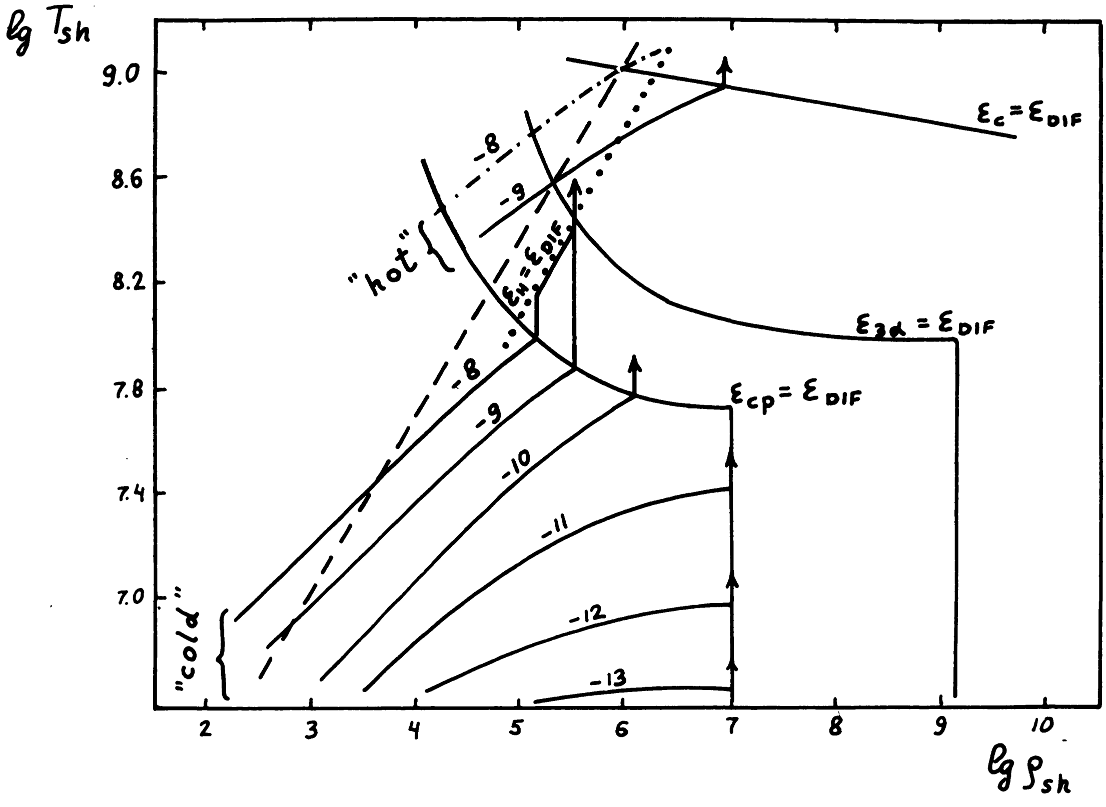

Fig. 1. Variation of temperature and density of the envelope of the accreting neutron star. The mass of the neutron star is 1.41 $M_\odot$ and the radius is 6.57 km. The numbers near tracks are the logarithm of the accretion rate in solar mass per year.

transforms to:

$$T_{sh} = \begin{cases} 10^{10.0}\left(\frac{\kappa\dot{M}}{M}\right)^{1/3}\left(\frac{\rho_{sh}}{\mu}\right)^{1/3} & \text{for nondegenerate gas} \\ 10^{8.75}\left(\frac{\kappa\dot{M}}{M}\right)^{1/4}\left(\frac{\rho_{sh}}{\mu_e}\right)^{5/12} & \text{for degenerate electron gas} \\ 10^{9.25}\left(\frac{\kappa\dot{M}}{M}\right)^{1/4}\left(\frac{\rho_{sh}}{\mu_e}\right)^{1/3} & \text{for relativistic degenerate electron gas} \end{cases} \quad (3)$$

These tracks are marked in Fig. 1 as "hot".

Equations (2) and (3) have been obtained under the assumption that

Table 1. Main parameters of nuclear bursts in the degenerate envelope of the neutron star
$M = 1.41\ M_\odot \quad R = 6.6\,10^{15}$cm

lg $\dot{M}$	lg E_{nuc} ergs	lg E_{He} ergs	lg T sec	lg τ sec	lg M_{sh} (g)	comment
- 9	40.0	-	5.5	2.0	22.3	hot
- 8	39.0	38.2	2.4	0.2	20.2	cold
- 9	39.0	38.2	3.4	0.2	20.2	cold
-10	40.0	39.2	5.4	1.2	21.2	cold
-11	41.2	40.4	7.6	2.4	22.4	cold
-12	41.2	40.4	8.6	2.4	22.4	cold
-13	41.2	40.4	9.6	2.4	22.4	cold
-14	41.2	40.4	10.6	2.4	22.4	cold
-15	43.4	43.4	14.6	5.4	25.4	cold

T is the interval between bursts, $\tau = \frac{E}{L_{ed}}$ is the duration of bursts, L_{ed} is Eddington luminosity, M_{sh} is the mass of the shell.

that the neutron star is a cold incompressible sphere with the low cooling energy flux. This assumption is consistent with the hypothesis that "bursters" are old neutron stars without a magnetic field. According to Tsuruta (1974) a hot neutron star cools very quickly and for $t \gtrsim 10^7$ years its temperature is less than 10^{7}°K.

Let us sketch the picture of thermonuclear burning in the shell for $\dot{M} \lesssim 10^{-9}\ M_\odot$/yr (see Fig. 1). The accretion leads to heating of the shell up to the "ignition" temperature of the reaction $C^{12}(P,\gamma)N^{13}$. That reaction heats the shell to 10^{8}°K (if $N_{CNO}/N_P \simeq 10^{-3}$). Stationary hydrogen burning becomes established 100 seconds later and the helium flash with a total energy release of more than 10^{38} ergs occurs at that moment if $\dot{M} \lesssim 10^{-9}\ M_\odot$/yr. The time interval between bursts exceeds one hour and the burst duration is equal to several seconds.

If the accretion rate exceeds $\sim 10^{-9}\ M_\odot$/yr, then the "hot" solution leading to accumulation of a carbon envelope becomes possible and bursts disappear. Thus, our simple model accounts for the main properties of observed X-ray bursters, although to get more information the numerical calculations are needed (Ergma, Kudryashov, 1979).

Let us now discuss briefly the problem of the origin of a close binary consisting of a neutron star in pair with a detached low mass main sequence star ($M \lesssim M_\odot$) with the distance between components of the order of $\sim 10^{11}$ cm. Tutukov and Yungelson (1979) found that such a system contracting due to gravitational wave radiation has a lifetime of $\sim 3\,10^9$ years and a mass exchange rate of $\sim 10^{-9} M_\odot$/yr which is responsible for the steady X-ray luminosity of bursters. But gravitational wave radiation becomes effective for a binary with solar mass components

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only if a $\lesssim 10^{11.3}$ cm. It is possible that the cold component with the strong magnetic stellar wind can lose its orbital angular momentum effectively if a $\lesssim 10^{12}$ cm (Eggleton, 1976, Kraitcheva et al., 1978), but we know that too poorly as yet. Taking into account that the galactic distribution of bursters is similar to the globular clusters' distribution, it seems probable that most of the prebursters were formed in globular clusters. After the tidal disruption of the latter, prebursters populated the bulge of our galaxy (Schakura, 1978) hence their galactic distribution.

We can point out two types of the recapture mechanism which can work in dense globular clusters according to Hills (1975). Hills found that if a binary collides with a star whose space velocity is smaller than the orbital velocity and the mass exceeds the mass of any component, then exchange capture is practically inevitable. The massive star forms a binary with the more massive component and the lightest star leaves the system. Supposing that half of all globular cluster stars are double we could estimate the number of close preburster systems forming in this way.

The total number of stars N_c of a cluster with the mass M_c in solar units and the Salpeter mass spectrum $dN \sim dM/M^{2.5}$ is $N_c = M_c/3m$, where m is the minimal mass of stars in solar mass. The number of stars with $M \gtrsim 10\ M_\odot$ N_S which become neutron stars through the supernova explosion is $N_S \approx 0.01\ m^{0.5}\ M_c$. Now on the grounds of simple statistics the number of close collisions which is supposed to be equal to the number of close captured binaries with semiaxes $a < a_{min}$ is:

$$n = \frac{v\tau N_s N_c a_{min}^2}{2R_c^3} \qquad (4)$$

where v is the average space velocity, τ is the lifetime and R_c is the cluster radius.

The number of binaries with $a_{min} \lesssim 10^{11.3}$ consisting of a neutron star and a low mass star formed during 10^{10} years in a cluster with $M_c = 10^6\ M_\odot$, $m \approx 0.1\ M_\odot$ and $R_c \approx 3$ pc is $n_1 \approx 0.3$. Such a close binary can leave the parent cluster due to the impulse conservation law. If the newly formed binary is wider, but a $\lesssim 100\ R_\odot$ and $M_{sec} \approx M_\odot$, then the secondary fills its Roche lobe in the course of its evolution. After the loss of part of the mass during the common envelope state of evolution a hydrogen model with a helium core will be established on a nuclear timescale. The mass loss rate will depend then on the initial period and values $\sim 10^{-9}\ M_\odot$/yr seem possible.

The second possibility is the formation of binaries with $a_{min} \lesssim 10^{13.6}$ cm consisting of a star with $M \gtrsim 10\ M_\odot$ and a low mass star. After expansion of the evolved massive component, the common envelope state (Tutukov, Yungelson, 1978) and the supernova explosion the system can become close enough for gravitational wave radiation (Paczynski, 1976). As $\tau = 10^7$ years in this case, the number of systems formed in the same cluster is $n_1 \gtrsim 12$. Taking into account the distribution of binaries over a we suppose that only part of them will turn out to be close enough. As the lifetime of the normal component filling the Roche lobe is $\sim 10^9$ years and the number of bursters ~ 30, the total number of prebursters previously formed in our galaxy is $\sim 3 \cdot 10^2$. Our estimations display a possibility of preburster close binary formation due to exchange capture, but uncertainties prevent improving these numerical estimations.

Let us note that the number of preburster binaries formed in the very center of our galaxy with $R \lesssim 100$ pc and $M \gtrsim 10^9\ M_\odot$, according to equation (4), three times exceeds this number for a rich globular cluster. So we can expect to find several burster-like systems in the very center.

Four sources with $L_X \gtrsim 10^3\ L_\odot$ in the center were found by Cruddace et al., 1978. Low luminosity of the optical counterpart is then due to its low mass and, possibly, due to the anisotrophy of disk X-ray radiation (Milgrom, 1978).

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