THERMONUCLEAR EXPLOSION IN BINARIES: WHITE DWARF HELIUM STAR

E.Ergma, A.V.Fedorova, A.M.Khohlov
Astronomical Council AS USSR
Pjatniskaja 48, 107019 Moscow, USSR

Abstract

Evolutionary sequences of a binary system consisting of a helium star in the stage of core helium burning and a white dwarf are presented. Different ways of He burning in the envelope of a dwarf are discussed. Incomplete helium burning is discussed with relation to occurence of possible observational features.

1. Introduction.

In a close binary system with a white dwarf component mass exchange is apparantly the unique mechanism leading to thermal instability and to the explosion of the white dwarf. Spherical-symmetric calculations of accretion on the white dwarf of matter with various chemical composition show that thermal instability occurs only for certain accretion rates and initial parameters of the binary (Iben and Tutukov, 1984).

In the case of hydrogen-helium accretion occurence of unstable hydrogen burning is highly probable. The most powerful hydrogen flashes may be connected with nova phenomeon (Gallegher and Starrfield 1984).

By carbon accretion conditions for Supernova explosions are realized in a wide range of mass accretion rates ($\dot{M} < 2\cdot10^{-6}$ $M_{\odot}$/yr, Nomoto and Iben,1985, Khohlov, 1985).But for stationary mass accretion during long time intervals it is necessary that the initial parameters of the binary satisfy the following conditions: 1) $M_1 + M_2 >$ >1.4 $M_{\odot}$, 2) $M_2 <$ 0.6 $M_{\odot}$ (Cameron and Iben, 1986). Although the scenario including systems with two degenerated CO dwarfs is very promising it is doubtful if the required number of such systems is enough (but see Iben and Tutukov, 1984)

https://doi.org/10.1017/S0252921100099693 Published online by Cambridge University Press

Analysis of observational data for SN I shows that they are not a homogenous class. At present one can state that there exsist SN Ia, SN Ib and besides a part of SNI spectra is impossible to classify (Branch, 1986, Filipenko and Porter, 1986). The possibility of other types of SN I although not so numerous can not be excluded.

In this paper we discussed the possibility of thermonuclear explosion in binaries with a helium star and a CO white dwarf. The observational behaviour of such a flash should be different from an explosive carbon burning case (for two degenerate CO dwarfs).

II. Necessary conditions for the realization of explosive helium burning in accreting CO dwarfs.

The investigation of He accretion on CO dwarfs has shown that almost indepently of the dwarf mass, if the mass accretion rate is less (2-3)$\cdot 10^{-8}$ $M_{\odot}$/yr helium burning starts at densities $> 10^{6}$ $g \cdot cm^{-3}$ (Taam, 1980a,b, Nomoto, 1986, Khohlov and Ergma,1989).

As was shown by Nomoto and Sugimoto (1977) for these densities helium burning is explosive (see also Mazurek, 1973).

It is necessary to determine which binaries have the required accretion rate (2 - 3)$\cdot 10^{-8}$ $M_{\odot}$/yr?

First there is the possibility of formation of double degenerate binaries with helium and CO dwarfs (Iben and Tutukov, 1984, 1986). But the required mass accretion rate is reached only when mass of the secondary is less than 0.1 $M_{\odot}$.

Second the evolution of a non-degenerate helium star with central helium burning filling its Roche lobe may provide the required accretion rate as it was shown by Savonije et.al (1986), Iben et al. (1987), and Fedorova and Ergma (1989).

Fedorova and Ergma have found that the accretion rate in the binary with a helium star and a CO dwarf is determined by two factors: 1) the mass relation $q = M_{He,2} / M_{CO}$, 2) the central helium abundance during the filling of Roche lobe by the secondary. On Fig.1 a plot of the mass transfer rate as a function of the mass of the secondary for a fixed mass of the system $M_1 + M_2 = 1.532$ $M_{\odot}$ is presented. As calculations show in the case q= 1 the accretion rate remains $2 \cdot 10^{-8}$ $M_{\odot}$/yr during several ten millions of years. Therefore it is possible to accumulate on the surface of a CO dwarfs a thick helium layer. For $q > 1$ mass accretion occurs from time to time with very high mass transfer rates.

3. Possible burning ways.

In the case of $\dot{M} < 4 \cdot 10^{-8}$ $M_{\odot}$/yr the condition for explosive helium burning can be realized when the density in the envelope is $(10^{6} - 10^{8})$ g cm^{-3} depending on the initial mass of the white dwarf.

https://doi.org/10.1017/S0252921100099693 Published online by Cambridge University Press

The mass of the white dwarf at that time must not necessary equal the Chandrasekar limit but may be much less. It is clear that for a mass transfer rate less than 10^{-8} $M_\odot$/yr and a larger initial mass of the CO dwarf unstable carbon burning may start in the center (Arnett, 1969 We are investigating the noncentral helium burning case.

He burning kinetics differ from the kinetics of carbon burning. The 3α reaction that provides C^{12} nuclei for the succeding - capture reactions ($C^{12} + \alpha$, $O^{16} + \alpha$,....., Ni^{56}) depens weakly on the temperature if $T \gtrsim (0.5 - 1) \cdot 10^9 K$ (Fowler et.al., 1975). For This Temperature range the helium burning time depens mainly on the density and may be approximated as (Khohlov, 1989)

$$\tau_{He} = \frac{12}{A^* \rho^2 \lambda_{3\alpha} Y^2_{He,0}} \left[\left(Y_{He,0} / Y_{He,1} \right)^2 - 1 \right] \quad (1)$$

where A^* is the mass number of α - capture products (see Khohlov and Ergma,1985) $\lambda_{3\alpha}$ is the 3α reaction rate (Fowler et.al. 1975), $Y_{he,0} = 0.25$ is the initial and $Y_{he,1}$ the final helium abundance (we assume that helium will be exhausted if $Y_{he,1} = 0.1\, Y_{he,0}$.)

$$\lambda_{3\alpha} = 2.79 \cdot 10^{-8} / T_9^3 \exp(-4.4027/T_9) \quad (2)$$

the width of the steady detonation wave in the helium is

$$\xi_{He,d} = D \rho_0 / \rho_s \, \tau_{He} (T_s, \rho_s) \quad (3)$$

where T_s, ρ_s are the temperature and density behind the front of shock wave, D - the velocity of detonation wave, ρ_0 - initial density of matter. For the Chapman-Joughe Detonation the dependence ρ_s, T_s and D with ρ_0 is (Khohlov, 1989).

$$\xi_{He,C-J} \simeq 4 \cdot 10^9 / \rho_0^{1.87} \ \text{cm} \quad (4)$$

By comparision of $\xi_{He,C-J}$ with the characteristic scale of the density change $L \sim \rho (d\rho/dr)^{-1} \sim 10^7$ cm it follows that for $\rho < 5 \cdot 10^6$ $g \cdot cm^{-3}$ $\xi_{He,C-J}/L > 1$. That means that for such values of densities the steady detonation wave although initiated will be destroyed On Fig.2 the distribution of density with Lagranian masses for various initial mass of the white dwarfs is presented. From this Fig. follows that for $M \lesssim 1\, M_\odot$ most of the white dwarf mass is below $\rho \sim$ $\sim 5 \cdot 10^6$ $g \cdot cm^{-3}$. For These dwarfs the incomplete helium burning may take place in the regime of deflagration or due to weak shock waves.

https://doi.org/10.1017/S0252921100099693 Published online by Cambridge University Press

The incomplete helium burning (as compared with burning in the detonation wave) may lead to a less energy production and hence smaller expansionvelocity. In more massive dwarfs ($M > 1M_\odot$) detonation is inevitable. Of course more Hydro-dynamic calculation with careful examination of the burning front in the thermal instability region is needed.

4. Possible observational consequences.

A. The expansion velocity may be estimated as

$$v = \sqrt{2 q M_b / M} \qquad (5)$$

where q -caloricity of the nuclear matter, M_b - the mass in which nuclear burning takes place. For $q = q_{He} = 1.5 \cdot 10^{18}$ erg/g and $M_b/M \sim$ $\sim$ (0.1-0.3) $M_\odot$ we obtain $v \simeq 10^4$ km/s that is observed in SN I.

B. The chemical composition in the case of explosive helium burning completly differs from that of explosive carbon burning. The explosive helium burning is determined by the characteristic time of (α, p), (α, γ) and (α,n) reactions on α-multiple nuclei (for example C^{12},O^{16},... Ni^{56}) and the rate of the 3α reaction (Khohlov, 1984, Khohlov and Ergma, 1986). On Fig.3 A^* is presented in dependence of ρ and T . During the whole burning the abundances of nuclei with $A <$ A^* and $A > A^*$ are very small. From Fig. 3 it is evident that the smaller the atomic weight of A nuclei between C and Fe (Si,S, Ca et.al) the larger densities and smaller temperatures are required for their synthesis. The dotted line on the figure presents ρ and T for explosive helium burning. It is clear that the formation of Si and S is practically impossible and the formation of Ca also meets with difficulties.

D. Incomplete burning means that the chemical composition of the expanding envelope may be helium and carbon+oxygen.

References.

Arnett W.D. 1969,Astrophys.Space Sci. 5,180
Branch D. 1986, Ap.J. 300, L51
Cameron A.G.W., Iben I.Jr. 1986, Ap.J. 305, 228
Gallagher J.S., Starrfield S. 1978, Ann. Rev. Astron. Astrophys,16,171
Fedorova A.V., Ergma E. 1989 Pisma Astron. Zh. (in press)
Filipenko A.V., Porter A.C. 1986 Palomar Observatory , Caltech Astrophysics preprint
Fowler W.D., Caughlan G.R., Zimmerman B.A. 1975 Ann. Rev. Astron. Astrophys. 13, 69
Iben I.Jr. Tutukov A.V. 1984 Ap.J.Suppl. 54, 535
Iben I.Jr., Tutukov A.V., 1986, Ap.J. 311, 742
Iben I.Jr., Nomoto K., Tornambe A., Tutukov A.V. 1987, Ap.J. 317,717
Khohlov A.M. 1984, Pisma Astron. Zh. 10, 297

https://doi.org/10.1017/S0252921100099693 Published online by Cambridge University Press

Khohlov A.M. 1985, Pisma Astron. Zh. 11,755
Khohlov A.M. 1989 Naycnye Inform. Asron. Council (in press)
Khohlov A.M/, Ergma E.V. 1985 , Astrophysika 23, 605
Khohlov A.M., Ergma E.V. 1989, Astrophysika (in press)
Mazurek T.J. 1973, Astrophys.Space Sci. 23, 365
Nomoto K. 1986, Ann. N.Y. Acad. Sci. 470, 294
Nomoto K., Iben I.Jr., 1985, Ap.J. 297, 531
Nomoto K., Sugimoto D. 1977, PASJ 29, 765
Savonije E.J., de Kool M., van den Heuvel E.P.J. 1986, Astron. Astrophys. 155, 51

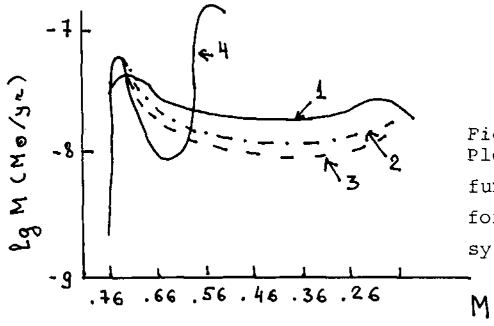

Fig.1
Plot of mass transfer rate as function of the secondary mass for an assumed fixed mass of the system 1.532 $M_{\odot}$ and Y_c = 0.97 (1),
= 0.658(2),
=0.413 (3),
= 0.097(4)

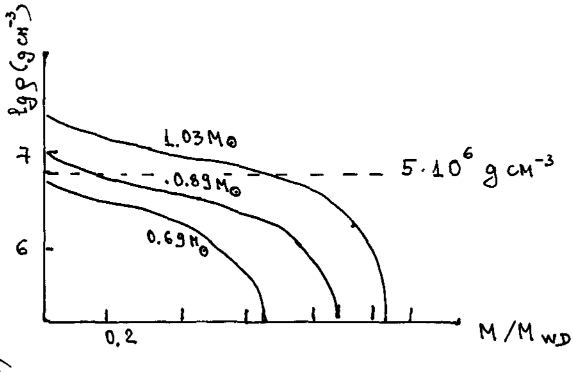

Fig. 2
Density distribution with lagrangian mass in the white dwarfs

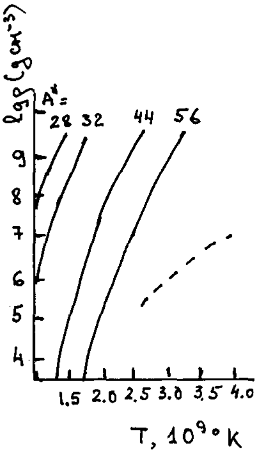

Fig.3
A^* = const lines in the (ρ ,T) plane for more abundant nuclei which are synthesized in explosive helium burning
The dotted line presents ρ and T for explosive helium burning

https://doi.org/10.1017/S0252921100099693 Published online by Cambridge University Press