ON EVOLUTIONARY MODELS FOR SNI PROGENITOR STARS

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ABSTRACT

It has been proposed that the Type I supernova (SNI) explosion starts in a white dwarf (WD) star that is accreting mass from a companion star in a close binary orbit. Others' computations have described this explosion, but how an accreting WD can ever become an SNI if it first ejects the accreted envelope in one or more nova outbursts is still unresolved. My calculations of WD evolution include the effects of mass accretion, convective mixing, nuclear burning, and gravitational settling. These calculations test the Starrfield, Truran, and Sparks (1981) proposal that at low accretion rates, settling of the CNO nuclei will lead to steady-state hydrogen burning, not nova outburst. The preliminary results of this study, consisting of two evolutionary sequences of an initially cool pure ^{12}C 1.0 $M_\odot$ WD show that nearly half of the carbon near the base of the accreted layer, initially of solar composition, gravitationally diffuses out in 2 x 10^5 years.

INTRODUCTION

Many researchers have proposed that the Type I supernova (SNI) explosion originates in a white dwarf (WD) star that is undergoing mass accretion from a companion star in a close binary orbit. Others' hydrodynamic computations describe the final result -- deflagration, off-center or central detonation leading to total disruption, growth toward the Chandrasekhar limit and gravitational collapse -- that depends primarily on the mass and composition (usually assumed uniform in shells) of the progenitor WD, the mass accretion rate, and the composition of the accreting matter. Nomoto (1980) has summarized the possible explosion scenarios (see his Table 1). All these computations assume that the SNI progenitor is an accreting WD, and thus address neither the question of how good the evidence is that SNIs come from an old population, nor whether the uniformity of observed characteristics of SNIs demand a single progenitor type.

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These computations also assume the structure of the pre-explosion WD. We still must resolve the following questions. 1) How does a given WD evolve to the pre-explosion configuration? 2) What is the most likely pre-explosion configuration, hence explosion mechanism? 3) How can an accreting WD ever evolve to a SNI if it first ejects the accreted envelope in one or more nova outbursts? Starrfield, Truran, and Sparks (1981) have proposed that because at low mass-accretion rates, gravitational settling of the CNO nuclei out of the accreted H envelope can occur on the accretion time scale or faster (Fontaine and Michaud 1979, Muchmore 1981), only steady-state hydrogen burning will occur, not nova outburst.

I have performed WD evolutionary calculations in an attempt to test the Starrfield et al. suggestion and to clarify these questions. The results of these calculations do not tell us anything fundamentally new about the SNI explosion mechanism, but do provide some much-needed detail about the composition morphology of the progenitor star, and apply some recent results on gravitational diffusion in WD stars to test directly the Starrfield et al. suggestion.

CALCULATIONS AND RESULTS

I used a modified version of Lamb's (1974) white dwarf evolution code based on a variant of the Henyey method described by Kippenhahn, Weigert, and Hofmeister (1967). The structure equations are integrated outward from the center, with mass fraction as the independent variable. The boundary conditions at logarithmic mass fraction -10^{-6} (approximately $10^{-6}\,M_\odot$ into the star) are computed by the method of triangles (Kippenhahn, Weigert, and Hofmeister 1967), starting with a grey atmosphere calculation, for which a radiative model atmosphere is integrated inward until it reaches a mass fraction chosen so that it coincides with an optical depth of about 1 to 10, or until it becomes convectively unstable according to the Schwarzchild criterion. The pressure and temperature at this depth constitute the surface boundary conditions for the envelope integrations used in the method of triangles.

I modified the code extensively to calculate the changing composition profile throughout the WD that results from mass accretion, convective mixing, nuclear burning, and gravitational settling. The initial model is a pure ^{12}C WD of mass $1.00\,M_\odot$, a luminosity of $L = 1.8 \times 10^{-4} L_\odot$, and an effective temperature of 7620K. The equation of state used for the fully ionized pure carbon shells in the interior of the star is taken from Lamb's (1974) work. It includes the effects of crystallization and the phase transition, electron exchanges, and Coulomb interactions in the liquid and solid phases, in addition to the usual expressions for semirelativistic, partially degenerate electrons. For the mixed composition shells in the partially ionized outer layers of the star (on either side of the boundary at logarithmic mass fraction -10^{-6}), I modified the code to compute thermodynamic properties for the mixed compositions by linearly interpolating in log T and log P in the equation of state tables of Fontaine, Graboske, and Van Horn (1977) and combining quantities as described by Colvin et al. (1977). In this

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study, the Iben I (X_H = 0.999), Iben V (X_{He} = 0.999), and Weigert V (X_C = 0.999) chemical compositions are treated as if they were pure H, He, and C, respectively. The table for the nearly pure carbon mixture is used to represent all elements collectively except H and He.

Mass accretion is accounted for by computing the amount of added mass given the time step and mass accretion rate, adding a new surface mass shell with this amount of mass, and rescaling all the other mass fractions accordingly. The composition of the accreted matter is specified independently.

Each mass shell is checked for convective instability by the Schwarzchild criterion, and, if convective, the temperature gradient computed from a standard mixing length theory, with the mixing length chosen as one half the pressure scale height. Composition in the convectively mixed regions of the star is computed as the mass fraction average of the individual compositions of the mass shells in the convection zone, including the accreted mass for the surface convection zone. This is a proper procedure as long as the convective time scale is short compared to the evolutionary time step, as it is for our models.

Energy generation is computed for all mass shells by the nuclear reaction network described by Starrfield _et al._ (1972). It includes energy losses resulting from neutrino emissivity (Beaudet, Petrosian, and Salpeter 1967). The energy generation and loss terms are included in the energy conservation equation, and composition changes resulting from nuclear reactions are also computed. Composition changes resulting from gravitational diffusion are computed using the scheme given by Fontaine and Michaud (1979). Diffusion velocities computed more recently by Muchmore (1981), by numerically integrating collision cross-section integrals including Debye potentials are in reasonable agreement with those of Fontaine and Michaud.

This is the first WD evolutionary calculation that includes all of the physical processes thought to be responsible for the composition morphology, while making use of the best available equation of state for WD matter.

The preliminary results of this study consist of two evolutionary sequences computed from the same starting model, one with gravitational diffusion and one without. Matter of solar composition (X=0.700, Y = 0.285) was assumed to accrete with spherical symmetry onto the WD at a rate of 10^{-11} $M_\odot$ yr^{-1}.

Note in Fig. 1 that the approximately isothermal core interior to the boundary at logarithmic mass fraction -10^{-6} remains unaffected by 2 x 10^5 years of accretion. In the outer layers of the star the effect of the accretion is to increase the pressure near the surface and to increase the temperature near the base of the accreted layer. The structure shown in Fig. 1 is for the sequence without gravitational diffusion. With diffusion the star is 10 K warmer and 10^{-6} $L_\odot$ brighter at the surface after 2 x 10^5 years because of the different opacities of the progressively hydrogen-rich material. This is a small effect on the star structure, but it has an interesting effect on the gravitational diffusion itself, as is seen in the next two figures.

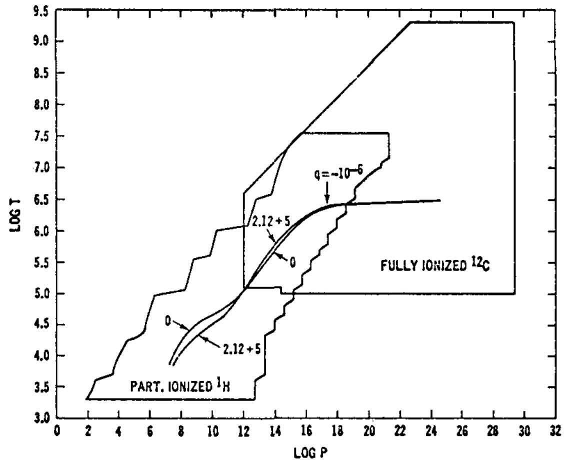

Figure 1. Star structure and EOS grids in log T - log P plane. $q = \log(M_r/M_*)$ is logarithmic mass fraction, with M_r the mass internal to radius r in a star of mass M_*.

In the first of these, Fig. 2, we see that in the initial stages of accretion, the effect of the added hydrogen-rich material is to suppress in part the convection. Thus, the convection zone retreats toward the surface as the accretion boundary moves inward, leaving behind regions of mixed composition, as first pointed out by Colvin et al. (1977). As the accretion boundary moves farther into the star we are left (for the case of no diffusion) with a growing region below the convection zone of matter containing 1.5 percent (by mass) carbon. This region is shown in much greater detail for the sequence including gravitational diffusion in Fig. 3. Here we see that in only 2 x 10^5 years nearly half the original carbon near the base of the accreted layer has diffused out. Thus, as diffusion proceeds, the opacity changes with the changing composition below the convection zone, the temperature goes up in the region, and because the diffusion coefficient increases with the 5/2 power of the temperature, the diffusion is hastened. What this means is that, at these low accretion rates, the CNO nuclei will settle out of the base of the accreted layer long before the approximately 10^{-4} $M_\odot$ of hydrogen-rich matter necessary for a nova outburst can accumulate, so the star can be expected to evolve to a SNI without going through a nova stage. This supposition, of course, needs to be tested with detailed calculations going to much later times.

As the accreted matter is pushed to higher densities in a WD as cool as the one considered here, however, the screening approximation on which the calculation of the diffusion velocities depends begins to break down, so the results (even for this case) may not be very accurate. It would be better to start with a hotter WD model, or, better still, to do a numerical plasma simulation to determine the transport properties of the cooler WD matter.

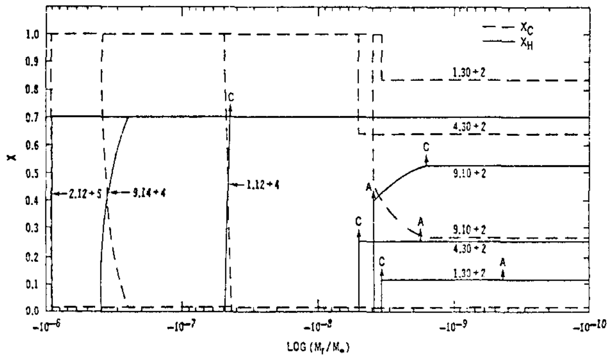

Figure 2. Hydrogen and carbon composition profiles vs logarithmic mass fraction at several times (no gravitational diffusion). "C" marks the position of the base of the convection zone, and "A" marks the position of the accretion boundary.

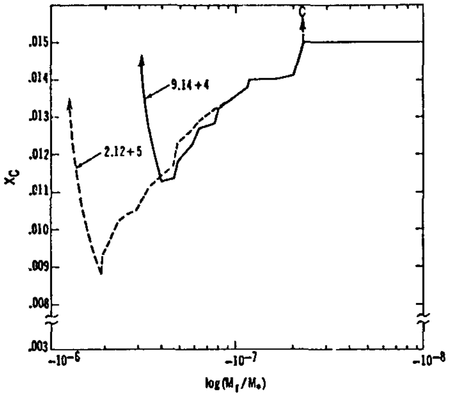

Figure 3. Details of carbon composition vs logarithmic mass fraction at several times, including gravitational diffusion.

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DISCUSSION FOLLOWING J. COLVIN'S TALK

WILLIAMS: At the beginning of your talk you mentioned that if you have a carbon-oxygen white dwarf and a high accretion rate and I think it was $5x10^{-8} M_{\odot}/yr$, you would expect helium shell flashes, can you elaborate?

COLVIN: This is taken from a paper that Nomoto presented at the type I supernova workshop in Austin two years ago. So this doesn't represent calculations that I have performed.

WILLIAMS: Does that mean that triple α occured in accretion onto a degenerate dwarf?

COLVIN: Yes, I believe that's what this means.

WILLIAMS: I have been asking other people if you can get that in that situation and they said, no.

SUGIMOTO: I think the answer should be as follows: When hydrogen accretes, a hydrogen shell flash takes place, hydrogen continues to accrete so that many hydrogen shell flashes are obtained. Then a part of the hydrogen is converted into helium and the helium zone grows until a helium shell flash takes place.

WILLIAMS: What if it was mainly helium that was accreted?

SUGIMOTO: The growth of the helium zone in mass by conversion of hydrogen by nuclear burning is the same as the accretion of helium.

SHAVIV: I would like to comment that the story with with CNO settling down is not clear. Because, if it is mixed by shear instabilities with the core, to give rise to a high CNO abundance, then the whole settling wouldn't occur. If the settling does occur and you get a layer of hydrogen which is CNO enriched at the bottom and CNO poor at the surface you might enhance the rate at which the thermonuclear runaway goes. Now will come the question what is seen in the ejecta. If the CNO is fully mixed we will observe solar abundance in most of the ejecta detonated by a small layer enriched with CNO. Hence the CNO abundance will change in time. The question of gravitational settling is not solved, because it will start to build up gradients that will try to annihilate it.

COLVIN: I agree. Comparing to observations depends upon the depth of the mixing. The settling is going to take place only below the mixed layer, so it is crucial how far down that mixed layer goes.

LAMB: If I understand how the gravitational diffusion occurs, to the extent that there is complete mixing of the outer layer of the star, the settling is enhanced. The settling rate increases as you go to higher densities. Therefore, if the outer layer of the star is mixed and brings unsettled material rapidly down to high densities and temperatures, then the heavy elements will actually settle out more quickly than if they had to diffuse all the way in from the outermost layers.

COLVIN: That's correct.