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A binary model for the progenitor of the supernova 1987a

ABSTRACT

We examine the hypothesis that the blue progenitor of SN1987A was a component of a close binary. The blue spectral appearance at the end of the core helium burning phase and later phases is the natural evolution for a star with initial mass of ≈ $12M_\odot$, which was the less massive component in a close binary with mass ratio $q \approx 1$, that accreted at least $8M_\odot$ during its hydrogen shell burning phase.

INTRODUCTION

Many scenarios have been suggested to explain the observed characteristics of the progenitor of 1987A, (see e.g. the review paper of Arnett et al. 1989) . The common ingredients used to explain its blue nature are: a low metallicity as observed in the LMC, the particular treatment of semiconvection, a process of induced mixing of core helium with the surrounding layers during late evolutionary stages of an original $20M_\odot$ star.

We examine the possibility that the progenitor of SN1987A was a component of a close binary in an earlier evolutionary phase. Model computations show that owing to accretion processes the characteristics of SN 1987A may be explained without inferring free parameters or artificial effects.

A BINARY MODEL

Processes increasing the fractional mass of the helium core (convective core overshooting during core hydrogen or helium burning, stellar wind mass loss at the red supergiant phase) favor redward motions in the HR diagram during hydrogen shell/core helium burning. Processes reducing this fractional mass will keep a hydrogen shell/core helium burning star in the blue SG-region. If furthermore such a process can form a hydrogen profile outside the helium core, assuring a large fuel supply for the H- burning shell during the final evolutionary phases, the star will remain blue up to the SN explosion. In a close binary such a process occurs in a natural way by accretion onto a H-shell burning star. The effects of accretion onto a hydrogen shell burning star have been studied by Hellings (1984). He computed the relaxation time and the further core He- burning evolution of a star after accretion . The H-profile and the He-core mass of an accreting H- shell burning star will only marginally change by accretion. As a consequence the core mass of a $12M_\odot$ star after accretion of $8M_\odot$ during H-shell burning will at the end of core He- burning be only slightly larger than the He-core of a 12-13 $M_\odot$ single star.

This accretion star has a very extended H-burning shell contributing more than 50 % to the total luminosity of the star during the whole core He- burning phase. Owing to the intermediate H- rich convective zone which develops on top of the H-burning shell, the massive accretion star remains in the blue part of the HR diagram during core He-burning .

These effects occur in binaries with a mass ratio very close to 1. In this case the gainer has already entered the H-shell burning phase when the donor star overflows its Roche lobe (RLOF). We propose the following evolutionary scenario (cfr. Joss et al., 1988):

The B3I progenitor of SN1987A is the accretion component in a close binary with initial mass ratio ≈ 1 and a period large enough for case B (C) of mass transfer.

RESULTS OF THE COMPUTATIONS

The evolution of a close binary system with initial masses 12 + $11.98M_\odot$ and with an initial period of 25 days was computed. The evolution of both components was followed simultaneously. RLOF was treated conservatively.To calculate the gravitational energy release in the interior of an accreting star we used the formalism of Neo et al. (1977). Semi-convection is treated using the neutrality condition of Schwarschild i.e. $\nabla = \nabla_{ad}$. For the determination of the boundary of the convective core we adopted a small overshooting parameter $\alpha=0.25$ (see Maeder and Meynet, 1987). Figure 1 shows evolutionary tracks for the mass loser and mass gainer.

DISCUSSION

Before the onset of the RLOF both components of the 12 + $11.98M_\odot$ close binary evolve in tandem. During the RLOF the system never goes into contact . At the end of the RLOF the loser is a H- deficient (X_{atm} < 0.3 by weight) core He-burning star of $3.2M_\odot$. It rapidly contracts towards the hot region in the HR diagram (log Teff ≈ 5) where it spends most of its core He-burning phase. At the end of its life the star is very compact, hydrogen deficient, hence a candidate for a type Ib explosion. We consider now the accretion star after mass transfer. When accretion stops (point 1 in figure 1), this star rapidly restores thermal equilibrium and evolves to the blue (point 2). Its relaxation time is of the order of 10^4 years. The mass of the gainer after accretion is $20M_\odot$. During the whole core He-burning phase this star remains in the blue part of the HR diagram. The interior structure the star at the end of core helium burning deviates considerably from that of a single $20M_\odot$ star at the same phase. The helium core mass is $4M_\odot$ and this fits the early day lightcurve better than the 7 - $8M_\odot$ core mass for a single $20M_\odot$ star (Maeder, 1991) .

Unlike for single stars the luminosity of an accretion star at the end of core He-burning is not exclusively determined by the mass of the He-core; also the H-shell contributes significantly to the total luminosity.

The total mass of the accretion star becomes considerably larger than the original mass of the primary of the binary; however the mass of the He- core does not increase in the same way. So the primary reaches the end of core He burning as yet before the accretion star.

The mass of the loser after RLOF is $3.2M_\odot$, hence large enough to undergo a SN explosion. The time lapse between the supernova explosions of the two components is ≈ 110.000 years. Hence around the year -108000 a first SN explosion may have occurred leaving a compact star.

Our computations were performed for a Galactic composition. However the blue nature of the progenitor of SN 1987A predicted by our computations will not be altered if a LMC composition will be used, since a smaller metallicity will help the star to remain blue during core helium burning.

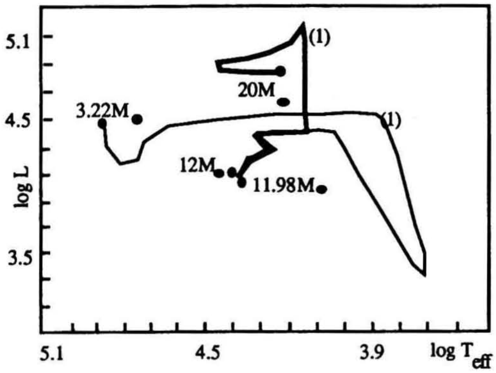
CONCLUSIONS

Case B evolution of close binaries with mass ratio close to one and primary masses between 12 - $15M_\odot$ may in a natural way explain blue SN progenitors. Our scenario does not depend on the metallicity, i.e. events like SN1987A could occur in the Galaxy as well.

The helium core mass of the accretion component in a close binary is smaller than the core mass of a single star of the same mass. Since during the last part of the RLOF, the gainer accretes matter which was CNO processed in the loser during its previous core hydrogen burning phase (≈ CN equilibrium abundances) we may expect a SN progenitor with altered (CNO) surface abundances.

The circumstellar shell around SN 1987A with altered CNO abundances observed by Fransson et al. (1989) has been used as an argument in favor of red supergiant evolution in single stars.

However the existence of this nitrogen- enhanced shell poses serious problems for single star computations when semi-convection is treated according to the formalism proposed by Langer (1991). In a binary such a circumstellar shell could be the result of a non conservative RLOF.



Evolutionary tracks for an initial system of $12+11.98M_\odot$ with initial period of 25 days

When mass is accreted, the gainer may acquire large angular momentum causing rapid rotation. The gainer may then enter a Be phase. As a consequence of this rotation matter which is transferred further on may be sweeped out of the system forming an asymmetric shell (asymmetry observed in the shell around SN 1987A).

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