# EVOLUTION OF STARS WITH $M \leqslant 8\,M_\odot$

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**Abstract.** The late stages of evolution of stars that develop degenerate carbon-oxygen cores are discussed. Model computations indicate that the initial masses of such stars, $M$, are below $M_1 = 8\,M_\odot \pm 2\,M_\odot$. The low mass stars ($M < M_0$) lose their envelopes and become white dwarfs. The intermediate stars ($M_0 < M < M_1$) ignite carbon in their highly degenerate cores of 1.4 $M_\odot$. Present observational and/or theoretical estimates of $M_0$ are very uncertain. Problems associated with mass loss and with carbon ignition and burning are discussed.

## 1. Introduction

Stars with the initial (i.e., main sequence) masses below 8 $M_\odot$ develop degenerate carbon-oxygen cores after hydrogen and helium exhaustion in their centers (Weigert, 1966; Arnett, 1969; Rose, 1969; Paczyński, 1970, 1971a; Uus, 1970, 1973) provided there is neutrino emission due to the universal Fermi interactions (UFI). This introductory paper is concerned with the final stages of evolution of such stars. It will be assumed that the UFI neutrinos are emitted. Most unfortunately, there are practically no model computations published so far which would follow the evolution of any star with $M < 8\,M_\odot$ all the way from the main sequence to the exhaustion of nuclear fuel, and in which the UFI neutrinos would be neglected. It should be stressed, therefore, that at the present time it is not possible to test the existence of the UFI neutrinos on the basis of comparison between the observed stars and the published models. In particular, nuclei of planetary nebulae cannot be used for such a test as long as realistic models without the UFI neutrinos are not available.

Final evolution of a model with $M < 8M_\odot$ and degenerate carbon-oxygen core is governed by the core mass. The larger the core mass, $M_c$, the larger the luminosity, $L$, produced by the hydrogen and helium shell sources. Model computations can be fitted with the following analytic formula

$$L/L_\odot = 59250\,(M_c/M_\odot - 0.522)\,, \tag{1}$$

which is good for $0.6 < M_c/M_\odot < 1.4$ (Paczyński 1971b). To maintain such a high luminosity, matter must flow from the hydrogen rich envelope through the shell source region into the degenerate core. Every gram of matter releases about $6 \times 10^{18}$ erg in this process, and therefore the rate of growth for the core mass is given as

$$\frac{\mathrm{d}M_c}{\mathrm{d}t}\,(M_\odot\,\mathrm{yr}^{-1}) \approx 10^{-11} L/L_\odot\,. \tag{2}$$

The envelope mass does not affect the nuclear burning and the luminosity of these models as long as it is larger than a certain limit, $M_{e,\mathrm{min}}$. Model computations

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(Paczyński, 1971b) give $M_{e,\min} = 3 \times 10^{-4}\, M_\odot$ for $M_c = 0.6\, M_\odot$, and $M_{e,\min} = 10^{-6}\, M_\odot$ for $M_c = 1.2\, M_\odot$. If the envelope is considerably more massive than $M_{e,\min}$ the star is a red supergiant and its effective temperature is in the range of 2000–3000 K. Given the luminosity and effective temperature the stellar radius may be calculated at once. Models show that red supergiants with $L > 10^4\, L_\odot$ or so have highly superadiabatic temperature gradients within the hydrogen and helium ionization zones that cover all the envelope, and the matter density is practically constant throughout a given envelope.

Degenerate carbon-oxygen cores have a structure similar to that of white dwarfs. As the core mass increases with time the core contracts slowly. The temperature at the centre is determined by the balance between the adiabatic heating and the cooling due to neutrino emission. Carbon is ignited when the central density rises up to about $2 \times 10^9$ g cm$^{-3}$ if the recent strong screening corrections are used (DeWitt *et al.*, 1973; Graboske *et al.*, 1973; Graboske, 1973). At that time the core mass is $1.38\, M_\odot$. Arnett (1969) suggested that carbon ignition leads to a detonation and a total disruption of a star. This problem was recently analyzed by Bruenn (1972) who gives a lot of references. It is possible that the neutrino energy losses due to the URCA process driven by convective motion stabilizes carbon burning and prevents a total disruption of a star (Paczyński, 1972; Couch and Arnett, 1973; Ergma and Paczyński, 1974) but this is not certain (Bruenn, 1973; Paczyński, 1974).

Let us suppose that the core mass does not grow up to $1.38\, M_\odot$ either because the total mass of a star was too small from the beginning, or the envelope was lost in a course of evolution. In this case the core becomes a carbon-oxygen white dwarf with a little of unburnt hydrogen left at the surface. On its way from the red giant to the white dwarf state the star evolves rapidly through the high luminosity–high temperature region of the HR diagram (Paczyński, 1970, 1971; Rose and Smith, 1970; Schwarzschild and Härm, 1973) which is occupied by nuclei of planetary nebulae. If the former stellar envelope is still present as a circumstellar matter at the time when the core evolves to the white dwarf state then the ultraviolet radiation from the core may ionize the circumstellar matter and a nebula may be seen. I think there can be little doubt that nuclei of young planetary nebulae are in a double shell source phase, as this is the only phase of evolution of a medium mass star when the luminosity in excess of $10^4\, L_\odot$ is achieved.

Schwarzschild and Härm (1965) discovered that helium shell burning around a degenerate core is thermally unstable and violent thermal pulses are produced in the stellar interior. Nobody was able so far to follow with the detailed model computations all the thermal pulses in a given stellar model, as too much computing time would be necessary. The impact of these instabilities on the stellar evolution is not really understood and it will not be discussed in this paper.

In the following discussion I shall concentrate on the two problems: mass loss from stars and carbon ignition and burning. I believe the other important aspect of stellar evolution, the large scale mixing which may bring to the stellar surface the products of nuclear burning, will be discussed by other speakers.

## 2. Mass Loss

The problem of mass loss from low or intermediate mass stars is closely related to the origin of planetary nebulae. Seventeen years ago Shklovsky (1956) convincingly suggested that planetary nebulae are formed from the envelopes of red supergiants. This idea is generally accepted now. Considering the high luminosity of nuclei of planetary nebulae it is clear that when a nebula is ejected the star must be in a phase of hydrogen and helium burning in two shells. There is no generally accepted mechanism for ejection of stellar envelopes, but a large number of different suggestions has been made. I shall discuss briefly those which seem to be the most common or plausible.

Helium shell flashes were frequently proposed to be the cause of envelope ejection. Perhaps the shell flashes do not drive but rather stimulate the mass loss (Smith and Rose, 1972). The envelopes of red supergiants may be unstable due to their own structure, as hydrogen and helium ionization zones are very thick. As a result an adiabatic exponent is smaller than $\frac{4}{3}$, and the total energy of an envelope is positive. It has been suggested (Lucy, 1967; Roxburgh, 1967; Paczyński and Ziółkowski, 1968) that envelopes are dynamically unstable. Nonadiabatic perturbations were recently studied by Smith and Rose (1972), Scott (1973), Sparks and Kutter (1972), and others. However, there is a very serious problem with all these suggestions and models. It is known that thermal and dynamical time scales for the envelopes of red supergiants are of the same order of magnitude, while the convective time scale is shorter than either thermal or dynamical time scale (Fawley, 1973). Therefore, we have to consider nonadiabatic motion of the envelope, and an interaction between the radial motion and convection must also be taken into account. There is no theory of such interaction. All investigators were forced to make (explicitly or implicitly) some ad hoc assumptions about this interaction and the results cannot be credible.

There is no compelling observational evidence that an ejection of an envelope is very rapid. Consider a young and dense planetary nebula. The electron density is hardly larger than $10^6$, and an ionized mass may be something like $10^{-2}\ M_\odot$. This corresponds to a nebular radius of $2 \times 10^{16}$ cm. If the original expansion velocity was 7 km $s^{-1}$ then the time scale for an ejection would be $10^3$ yr, and the implied mass loss rate only $10^{-5}\ M_\odot\ yr^{-1}$. This is not much more than an average mass loss rate which is observed in a typical Mira variable $-2 \times 10^{-6}\ M_\odot\ yr^{-1}$ according to Gehrz and Wolf (1971). It is possible that the steady mass loss that is observed to be taking place in red supergiants is a process responsible for an ejection of a whole envelope and a formation of a planetary nebula (Paczyński, 1971c). Radiation pressure on dust grains formed in the atmosphere may be the driving force (Weymann, 1962; Wickramasinghe *et al.*, 1966; Krishna Swamy and Stecher, 1969; Balamore and Lucy, 1972; Gilman 1972). No satisfactory model has been published so far but this approach seems to be promising.

It is frequently suggested that the driving force for mass loss may be the radiation pressure in the high opacity regions where hydrogen and helium are partly ionized.

Models with a stationary mass loss were considered by Finzi and Wolf (1971), Bisnovaty-Kogan and Nadyozhin (1972) and many others. Unfortunately, Żytkow (1972, 1973) has shown that in such models the transition from a subsonic to a supersonic flow takes place below the photosphere, where the gas density is high. As a result the mass loss rates obtained from the models are so large that the process cannot be stationary. Therefore, we come back to the problem of interaction of radial motion with convection, and this approach seems to be hopeless at present.

Little is known observationally about the range of masses of planetary nebulae, but the range is likely to be very large. It should be stressed that there is no observational evidence that all nebulae have identical masses, say 0.2 $M_{\odot}$ or 0.6 $M_{\odot}$, though 0.2 $M_{\odot}$ may very well be a median value. A typical mass of the ancestor star is believed to be 1 $M_{\odot}$ or 1.5 $M_{\odot}$, but nothing is known about an upper mass limit. Frequently, when a circumstellar nebula is discovered to have a mass of say 10 $M_{\odot}$ it is immediately said not to be a planetary nebula as its mass is too large.

Nuclei of planetary nebulae evolve towards the white dwarf stage. One may try to estimate the range of stellar masses for which the mass loss is important by studying white dwarfs in open clusters. Jones (1970) estimated that stars with $M \leqslant 2 M_{\odot}$ were producing white dwarfs. One may also assume that stars above a certain mass limit $M_0$ explode as supernovae, while the less massive stars lose enough matter to become white dwarfs. With the known (?) rate of supernova explosions and the known birth rate function the value of $M_0$ may be deduced. I believe that different authors gave estimates that ranged from 3 $M_{\odot}$ up to 10 $M_{\odot}$. This simply reflects the uncertainty of the statistical approach.

Considering the present status of the theory of mass loss and the present state of interpretation of the observations, it is fair to say that we do not know what is the value of $M_0$, the limit that separates the low mass stars which produce white dwarfs (and presumably planetary nebulae), and the medium mass stars which can ignite carbon in their 1.4 $M_{\odot}$ degenerate cores. If there was no mass loss such cores could be produced by stars in the mass range of $1.4 M_{\odot} - M_1$, where $M_1$ is believed to be about 8 $M_{\odot}$. This upper mass limit is derived from the model computations only, and these computations are sensitive to the efficiency with which the convective envelope can penetrate the helium core. My impression is that we have $M_1 = (8 \pm 2) M_{\odot}$, and I would like to stress the likely uncertainty which places $M_1$ somewhere in the range of 6–10 $M_{\odot}$. It is not impossible that in fact we have $M_1 < M_0$, and that there are no stars igniting carbon in their degenerate cores (Arnett, private communication)!

## 3. Carbon Ignition and Burning

Let us consider now carbon ignition in degenerate cores, assuming that there are stars in which this process is taking place. According to Arnett (1968, 1969) carbon ignition leads to a detonation and a supernova explosion, and no stellar remnant is left. On the other hand it has been suggested by Gunn and Ostriker (1970), on the basis of a statistical analysis of the observational data, that the ancestors of pulsars should be stars in the main sequence mass range of 4–10 $M_\odot$. This suggestion created a demand for finding a physical process that could prevent a total disruption of a star undergoing carbon ignition within the degenerate core (Arnett, 1971; Barkat *et al.*, 1971, 1972; Buchler *et al.*, 1971; Bruenn, 1971, 1973a, b; Colgate, 1971; Paczyński, 1972, 1974; Sackmann and Weidemann, 1972; Iben, 1972; Couch and Arnett, 1973; Ergma and Paczyński, 1974). Energy losses due to convectively driven URCA processes are likely to prevent carbon detonation. Simplified models of Ergma and Paczyński (1974) indicate that it may be possible to exhaust carbon nonexplosively within the inner 0.5 $M_\odot$ of the core. Perhaps the inner core may then collapse and produce a neutron star of about 0.5 $M_\odot$, while the outer 0.9 $M_\odot$ of the core would explode due to carbon detonation.

It is unfortunate that the available model calculations are crude and the results are uncertain. At the same time it is no longer clear that pulsars have to be produced from the medium mass stars. Arnett and Schramm (1973) suggest that pulsars are produced by massive stars ($8 \leqslant M/M_\odot \leqslant 70$). These stars have about the same death rate as the medium mass stars ($4 \leqslant M/M_\odot \leqslant 8$) (cf. Salpeter, 1959; Schmidt, 1963). This new suggestion is reasonable as Arnett demonstrated that all massive stars are developing 1.4 $M_\odot$ central cores.

Sometimes it was argued that carbon detonation models would produce too much iron peak elements in the Galaxy. This is not obvious, as the explosions of massive stars may produce mostly elements from carbon to silicon (Arnett and Schramm, 1973); the mass ejected per explosion is larger than it is in a medium mass star, while the number of explosions may be comparable. If we notice that the cosmic abundance ratio Fe/(C+O+N) is about $\frac{1}{4}$ (Allen, 1955) then it becomes clear that the present day theory of late stages of stellar evolution combined with statistical arguments can, at the best, narrow the range of masses for which carbon ignition is disruptive. There is no obvious reason to believe that carbon detonations are incompatible with the observations. Perhaps studies of individual pulsars and supernova remnants are more promising in determining the origin of pulsars than the statistical analysis is.

## 4. General Discussion

In this paper I intended to demonstrate that the two most fundamental processes for the late stages of evolution of intermediate mass stars ($M < 8\ M_\odot$) are not theoretically understood, and that the interpretation of existing observations does not provide us with the answers we need. The two processes are the mass loss and carbon ignition. I believe that more effort should be made to interpret the observations and to verify observationally existing models of double shell source stars. One obvious theoretical prediction is the luminosity function for red supergiants that are in a double shell source phase. Combining the Equations (1) and (2) we obtain for the rate of change of a bolometric magnitude

$$\frac{dM_{\text{bol}}}{dt} = -6.4 \times 10^{-7}\ \text{yr}^{-1}, \tag{3}$$

for $-7.0 < M_{\rm bol} < -4.4$, which corresponds to $1.4 > M_{\rm core}/M_\odot > 0.6$. If all stars went through this range of the carbon-oxygen core masses the luminosity function would be constant. Loss of an envelope stops the core growth and may produce a deficiency of the most luminous supergiants.

Analysis of luminous infrared objects and objects suspected of being young planetary nebulae may provide us with an information about the time scale on which an envelope of a red supergiant is lost. A deep photograph of NGC 6543 (Millikan, 1972) shows a large faint nebulosity, 5′ in diameter, and the inner bright nebulosity, only 0′.5 in diameter. This may indicate that the rate of mass loss was variable, small in the past and large at the final phases.

There is a very spectacular variable star, FG Sge, which is a nucleus of a planetary nebula (Herbig and Boyarchuk, 1968; Langer *et al.*, 1973). This star probably undergoes a thermal pulse in its helium shell source (Paczyński, 1971b). As the luminous nuclei of young planetary nebulae are almost certainly in a double shell burning phase of evolution many of them should exhibit light variations on the time scale of years or decades. Theoretical timescales can be calibrated by means of model computations in terms of core and envelope masses. Observations could be used to check the models and to derive masses of the nuclei of planetary nebulae.

Type I supernovae are believed to explode in galaxies where there are no massive stars. There are suggestions (see e.g. Finzi and Wolf, 1967) that presupernovae of type I are white dwarfs with masses very close, but smaller than the effective Chandrasekhar mass limit. Supposedly such white dwarfs could be produced some $10^9$ or $10^{10}$ yr ago, when there were massive stars available. On a long time scale either the white dwarf mass was increasing, or the effective Chandrasekhar mass limit was decreasing. Such an evolution could finally lead to an explosion. The best candidates for the ancestors of massive white dwarfs are the intermediate mass stars. In this case the initial conditions for a presupernova model may be obtained from the model calculations for the evolution of an ordinary star (Paczyński, 1971a). It is essential to have better knowledge about the pycnonuclear reaction rates and other physical properties of dense matter at low temperature. Evolutionary calculations for hypothetical type I presupernovae could link the theory of intermediate mass stars with the theory of supernovae.

Interaction between the convection and URCA processes is essential for carbon burning in degenerate matter and a consistent picture of this interaction is needed in order to be able to predict theoretically the final products of the evolution of intermediate mass stars.

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