Core–Halo Structure of a Chemically Homogeneous Massive Star and Bending of the Zero–Age Main–Sequence

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Abstract

We have recalculated the interior structure of very massive stars of uniform chemical composition with the OPAL opacity. Very massive stars are found to develop a core–halo structure with an extended radiative–envelope. With the core–halo structure, because a more massive star has a more extended envelope, the track of the upper zero–age main-sequence (ZAMS) curves redward in the H–R diagram at $L > 100 M_\odot$ ($Z = 0.02$), $> 70 M_\odot$ ($Z = 0.05$), and $> 15 M_\odot$ for helium ZAMS ($X = 0$, $Z = 0.02$). Therefore, the effective temperatures of very massive ZAMS stars are rather low: e.g., for a 200$M_\odot$ star, $T_{\text{eff}}$ = 4.75 ($Z = 0.004$), 4.60 ($Z = 0.02$), 4.46 ($Z = 0.05$), and 4.32 ($Z = 0.10$). The effective temperatures of very luminous stars ($> 120 M_\odot$) found in the LMC, the SMC, and the Galaxy are discussed in relation to this metal dependence of a curving upper main-sequence.

Key words: Stars: abundances — Stars: individual(the Pistol star) — Stars: interiors — Stars: massive — Stars: supergiants

1. Introduction

Recent infrared observations have found a number of very luminous stars in young clusters near to the galactic center, in 30 Doradus in the LMC and in star-forming regions in the SMC (Nagata et al. 1993, 1995; Najarro et al. 1997; Messey, Hunter 1998). The Pistol star, a member of the AFGL 2004 young cluster (Nagata et al. 1993; Figer et al. 1996), is one of the brightest stars known in the local group of galaxies. The luminosity and the temperature of the Pistol star were derived to be $L(L_\odot) = 6.6$ and $T_{\text{eff}}(K) = 4.15$, respectively, from a near–infrared data analysis (Figer et al. 1998). Very luminous stars with such a low surface temperature are rarely found in conventional observations, which stimulates a theoretical interest in its evolutionary stage. Compared with the evolutionary path of very massive stars in the H–R diagram, Figer et al. have derived the initial mass of the Pistol star to be 200–250$M_\odot$ and the age to be 1.7–2.1 Myr. In the LMC, there also found a number of very luminous O3 stars in the R136 cluster in 30 Dor, several of which have a mass in excess of 120$M_\odot$ (Messey, Hunter 1998). One of them, Melnick 42, is analyzed in detail by Pauldrach et al. (1994), who estimate the luminosity and the mass of the star to be $L(L_\odot) = 6.6$ and $M = 150 M_\odot$.

In this way, very luminous stars are found in various chemical circumstances. Their inferred mass, age, and evolutionary status provide fundamental information for studies of star–forming regions. In order to estimate their age and mass, we require theoretical tracks of very massive ($> 120 M_\odot$) MS stars of both Populations I and II. With the discovery of the very massive stars ($L > 10^6 L_\odot$) mentioned above, we need to reanalyze the structure of very massive MS stars.

Kato first found from an analysis that very massive stars develop a core–halo structure, which results in a redward bending of the upper main–sequence. Kato (1985) calculated the structures of very massive Newtonian stars with Compton–scattering opacity, and found that vary massive stars develop an extremely extended radiative envelope. Such a structure is caused by an outward increase of the opacity in the radiative region. With the Compton–scattering opacity, this core–halo structure appears only in very massive stars ($> 10^6 M_\odot$). When a star develops a core–halo structure, the photospheric temperature decreases owing to the extended envelope. Because a more massive star has a more extended envelope, the upper part of the main–sequence curves to the right in the H–R diagram at very high luminosity, $L > 10^6 L_\odot$, for Pop I (Kato 1986). Such a massive star of $\sim 10^8 M_\odot$ may be a theoretical problem rather...
than a realistic one; but after the new opacity, we ex-
pect that the core–halo structure and the resultant main–
sequence bending will be realized in much less–massive
stars. This is because the Compton–scattering opacity
increases outward only a few percent in the radiative re-
gion, whereas the new opacity has a prominent peak at
around \( T \sim 2 \times 10^5 \) K that must cause the structure to
change effectively.

The bending of the main–sequence appears for a much
smaller mass in the case of helium stars with the Los
Alamos radiative opacity. Langer (1989) has calcu-
lated chemically uniform helium stars with central he-
lium burning as models of Wolf–Rayet stars. The pure
helium main–sequence \( (Y = 1.0) \) only indicates bend-
ing at \( > 60M_{\odot} \), but sequences of C/O–rich helium stars
curve rightward in less–massive stars (e.g., at \( \geq 15M_{\odot} \)
for \( Y = 0.02, C + O = 0.98 \)). The bending appears in
less–massive C/O–rich stars because of a larger radiative
opacity of C/O–rich matter.

The core–halo structure is also reported in helium
main–sequence stars with optically thick winds. Kato
and Iben (1992) have presented the interior structure
of helium main–sequence stars with artificially enhanced
opacity in a model of Wolf–Rayet stars. The core–halo
structure is developed in stars of mass 15 – 30 \( M_{\odot} \), in
which the radiative envelope is extended in a way that the
density profile changes while responding to any opacity
variation. In the H–R diagram, the main–sequence runs
from the lower–left to the upper–right, contrary to the
usual main–sequence. This main–sequence corresponds
to the upper half part of the curved main–sequence
described above.

In this way, chemically homogeneous stars show a
core–halo structure which results in the curved main–
sequence when the opacity monotonically increases out-
ward. The new opacity, which varies around a prominent
peak, requires a recalculation of the core–halo structure
and bending of the main–sequences. Therefore, we have
recalculated the interior structure of very massive main–
sequence stars with the OPAL opacity. After the new
opacity appeared, there have been presented many cal-
culations on massive–star evolution for various problems,
such as evolution with wind mass–loss, instability against
radial oscillation, WR star modeling, evolutionary con-
nection between O stars, LBV, and WR stars etc. (e.g.,
Schaller et al. 1992; Heger, Langer 1996; Glatzel, Kiri-
akidis 1998; Stothers, Chin 1996, 1997, and references
therein); but little attention has been paid to the core–
halo structure and the resultant bending of the main–
sequence. The main–sequence up to 120 \( M_{\odot} \) shows no
indication to turn to the right for \( Z \leq 0.02 \), (Schaller et al.
1992), and it slightly does so for \( Z = 0.03 \) (Glatzel, Kiri-
akidis 1993); however, more massive stars up to 300 \( M_{\odot} \),
ZAMS curves redward at \( \geq 120M_{\odot} \) for \( Z = 0.02 \) and
0.04 (Figer et al. 1998). In the present paper, we have
concentrated on massive zero–age main–sequence stars
in order to examine the basic properties of the core–halo
structure and to confirm the bending of MS. The next
section describes the method and assumptions of the nu-
merical calculation, and section 3 shows the core–halo
structure of chemically homogeneous stars and presents
curved ZAMS for Populations I and II in the H–R di-
agram. A comparison with observational data of very
luminous stars, such as the Pistol star, is given in discus-
sions.

2. Calculations

The structure of massive stars with uniform chemical
composition is obtained by solving the equations of
hydrostatic balance, mass continuity, energy transfer
by diffusion and by convection, and energy conserva-
tion with the assumption of spherical symmetry. We
 calculated two sets of ZAMS solutions, i.e., with/without
mass–loss. The wind mass–loss is assumed to be in the
quasi–steady state in which the heat flux is steady in the
\( q \)–coordinate, i.e., the gravitational contraction term
in the energy–conservation equation is approximated by
\( \varepsilon = -T(M/M)\delta s / \delta \ln q \), where \( q = M/M \) is the
mass within radius \( r \) divided by the stellar mass, and
the suffix \( t \) denotes the partial derivative with constant
time. These equations and assumptions are essentially
the same as those in Kato (1980). This quasi–steady
state condition stands well for a chemically uniform star
with mild mass–loss. We have checked it by reproducing
the diffusive luminosity distribution obtained by a hy-
drodynamic calculation for a 15 \( M_{\odot} \) He MS star (Heger,
Langer 1996). The wind mass–loss rate is assumed to be
zero and \( 5 \times 10^{-5} M_{\odot} yr^{-1} \) for MS stars. Because
of the effects of wind mass–loss on the stellar structure
is very small, the interior structure hardly changes up
to \( 1 \times 10^{-4} M_{\odot} yr^{-1} \): the effective temperature increases
only by \( \Delta \log T_{\text{eff}} = 0.003 \) if we include a mass loss of
\( M = 1 \times 10^{-4} M_{\odot} yr^{-1} \) in the 200 \( M_{\odot} \) model. The up-
dated OPAL opacity (Iglesias, Rogers 1996) is used and
the mixing–length parameter for convective energy trans-
port is set to be 1.5. The chemical composition of stars
is assumed to be uniform with \( X = 0.7 \) for hydrogen,
and \( Z = 0.004, 0.02, 0.05, \) and 0.1 for heavy elements by
weight. In addition to these compositions, we have calcu-
lated additional models with different combination for a
comparison: \( X = 0.35 \) and \( Z = 0.05 \), and helium ZAMS
of \( X = 0, \) and \( Z = 0.004, 0.02, 0.05, \) and 0.1 without
mass loss.

3. Interior Structure of Massive Stars and the
H–R Diagram

Figure 1 shows the distributions of the density and the
temperature of chemically homogeneous stars of 40 and
Fig. 1. Temperature and density distributions of chemically uniform stars \((X = 0.7, Z = 0.02)\) of 40 and 200 \(M_\odot\) (solid curve). The dot denotes the outer edge of the convective core. The outermost point of each curve denotes the photosphere. The dashed and dotted curves denote the stars of 200 \(M_\odot\) with \((X = 0.7, Z = 0.004)\) and \((X = 0.7, Z = 0.10)\), respectively.

200\(M_\odot\) for \(Z = 0.02\). The 200\(M_\odot\) star has a quite different structure from the 40\(M_\odot\), because it develops an extended isothermal radiative–envelope where the density is almost constant. Such a core–halo structure develops well in very massive stars \((> 150M_\odot)\), but does not do so in less–massive stars, such as the 40\(M_\odot\), as shown in this figure. These two different types of homogeneous stars have already been pointed out by Kato (1985). Following her way, we call the core–halo structure a Type–II solution, and for the other one, the usual structure like in a 40\(M_\odot\) star, a Type–I solution.

Figure 2 shows the distributions of the diffusive luminosity, the local Eddington luminosity,

\[
L_{\text{Edd}} = \frac{4 \pi c G M_r}{\kappa},
\]

and the opacity. As shown in this figure, the local Eddington luminosity decreases outward in the radiative region, corresponding to an increase of the OPAL opacity toward the peak at \(T \sim 2 \times 10^5\) K. The 200\(M_\odot\) star shows the super–Eddington luminosity in the outer radiative region, where the convective heat transport is inefficient and a wide isothermal region develops to form a core–halo structure, as shown in figure 1. In the 40\(M_\odot\) model, the diffusive luminosity does not reach the Eddington luminosity in the radiative region, and thus no core–halo structure appears.

We also calculated the structures of helium ZAMS stars \((X = 0.0)\) and helium–rich stars \((X = 0.35, Z = 0.05)\). Type–II solutions also appear in these stars, and their basic properties are the same as those in ZAMS stars. Figure 3 shows the density and the temperature distributions for helium stars of 12 and 40\(M_\odot\); the latter shows the core–halo structure.

Such a core–halo structure is more extended in metal–rich stars. Figure 1 demonstrates the difference of interior structures of a 200\(M_\odot\) star with various metal contents, \(Z = 0.004, 0.02, \) and 0.10. Metal–rich stars develop a wide isothermal radiative envelope. As the envelope is most extended, the effective temperature of the star is the lowest of these three stars.

Table 1 gives the physical quantities of solutions for very massive stars with various sets of chemical composition, \(X\) and \(Z\). The four columns next to \(Z\) give the photospheric values of the radius \(R_{\text{ph}}\), temperature \(T_{\text{ph}}\), luminosity \(L_{\text{ph}}\), and ratio of the diffusive luminosity to the Eddington luminosity at the photosphere \(L_{\text{ph}}/L_{\text{Edd}}\).
Table 1. Characteristic values of very massive star.

| Mass ($M_{\odot}$) | X   | Z   | $R_{\text{ph}}$ ($R_{\odot}$) | $\log T_{\text{ph}}$(K) | $\log L_{\text{ph}}/L_{\odot}$ | $L_{\text{ph}}/L_{\text{Edd}}$ | 1-$(M_{\text{c}}/M)$† | log $T_{\text{c}}$ (K) |
|---------------------|-----|-----|-----------------------------|----------------------|-------------------------------|--------------------------|----------------------|------------------|
| 40                  | 0.7 | 0.02| 9.3                         | 4.62                 | 5.35                          | 0.65                     | 0.38                 | 7.57             |
| 60                  | 0.7 | 0.02| 12                          | 4.65                 | 5.71                          | 0.74                     | 0.28                 | 7.59             |
| 100                 | 0.7 | 0.02| 18                          | 4.67                 | 6.11                          | 0.84                     | 0.19                 | 7.61             |
| 200                 | 0.7 | 0.02| 40                          | 4.60                 | 6.57                          | 0.92                     | 0.091                | 7.63             |
| 250                 | 0.7 | 0.02| 55                          | 4.57                 | 6.71                          | 0.95                     | 0.077                | 7.63             |
| 300                 | 0.7 | 0.02| 71                          | 4.54                 | 6.82                          | 0.96                     | 0.066                | 7.63             |
| 500                 | 0.7 | 0.02| 160                         | 4.44                 | 7.10                          | 0.97                     | 0.042                | 7.65             |
| 1000                | 0.7 | 0.02| 3000                        | 4.08                 | 7.46                          | 0.95                     | 0.029                | 7.66             |
| 100                 | 0.7 | 0.05| 26                          | 4.58                 | 6.09                          | 0.87                     | 0.19                 | 7.58             |
| 200                 | 0.7 | 0.004| 20                         | 4.75                 | 6.58                          | 0.87                     | 0.096                | 7.66             |
| 200                 | 0.7 | 0.05| 76                          | 4.46                 | 6.56                          | 0.93                     | 0.091                | 7.60             |
| 200                 | 0.7 | 0.1 | 140                         | 4.32                 | 6.55                          | 0.89                     | 0.10                 | 7.58             |
| 40                  | 0.35| 0.05| 15                          | 4.59                 | 5.68                          | 0.85                     | 0.24                 | 7.58             |
| 100                 | 0.35| 0.05| 75                          | 4.41                 | 6.34                          | 0.86                     | 0.10                 | 7.62             |
| 150                 | 0.35| 0.05| 200                         | 4.26                 | 6.59                          | 0.89                     | 0.073                | 7.63             |
| 8                   | 0.02| 0.82| 0.82                        | 5.04                 | 4.94                          | 0.73                     | 0.41                 | 8.13             |
| 12                  | 0.02| 1.1 | 1.1                         | 5.07                 | 5.29                          | 0.88                     | 0.32                 | 8.28             |
| 15                  | 0.02| 1.3 | 1.3                         | 5.08                 | 5.47                          | 0.93                     | 0.28                 | 8.30             |
| 30                  | 0.02| 8.3 | 8.3                         | 4.79                 | 5.96                          | 0.94                     | 0.18                 | 8.31             |
| 40                  | 0.02| 20  | 20                          | 4.64                 | 6.14                          | 0.97                     | 0.15                 | 8.32             |
| 60                  | 0.02| 71  | 4.43                        | 6.38                 | 0.80                          | 0.12                     | 8.33                 |
| 100                 | 0.02| 670 | 6.02                        | 6.67                 | 0.02                          | 0.096                    | 8.36                 |
| 130                 | 0.02| 850 | 4.00                        | 6.81                 | 0.017                         | 0.087                    | 8.36                 |
| 40                  | 0.004| 2.2 | 5.13                        | 6.14                 | 0.99                          | 0.15                     | 8.32                 |
| 40                  | 0.05 | 130 | 4.25                        | 6.14                 | 0.81                          | 0.15                     | 8.32                 |

* The ratio of the photospheric luminosity to the Eddington luminosity at the surface.
† The ratio of the mass of the radiative envelope to the total stellar mass.
The next gives the ratio of the mass of the radiative envelope to the total stellar mass, $\frac{1 - (M_c/M)}$, where $M_c$ denotes the mass of the convective core. The last column gives the central temperature $T_c$ of the star.

In the main–sequence with $(X = 0.7, Z = 0.02)$ in table 1, $T_{\text{ph}}$ increases with the stellar mass until it has the maximum value at $\sim 100 M_\odot$, and decreases after that as the core–halo structure develops. Here, we define the critical mass which divides the Type–I and Type–II solutions as the stellar mass of the maximum effective temperature in each sequence. This critical mass is tabulated in tables 2 and 3, for ZAMS and He–ZAMS, respectively.

Figure 4 shows four tracks of ZAMS with $X = 0.7$, and $Z = 0.004, 0.02, 0.05$, and 0.10, left to right, in the H–R diagram. The metal–poor main–sequence ($Z = 0.004$) curves slightly rightward at $\geq 300 M_\odot$, while the metal–rich sequences curve strongly at above several tens of $M_\odot$. This is because the core–halo structure develops well in metal–rich stars, and the effective temperature is lower than that of the metal–poor star with the same mass. Therefore, the effective temperature depends strongly on the metal contents, while the luminosity depends weakly on the metallicity, as shown in figure 4.

Figure 5 depicts $U–V$ curve of the stars of 40, 200, and as the extreme massive case 1000 $M_\odot$, to demonstrate the difference of in the interior structures of the Type–I and Type–II solutions, where $U$ and $V$ are the homologous invariants, defined by

$$U = 4\pi r^3 \rho/M_r$$

and

$$V = GM_r\rho/(rP).$$

Here, $U$ represents the density divided by the mean density, and $V$ is the ratio of the gravitational energy to the thermal energy. A Type–I solution, such as of the 40$M_\odot$ main–sequence star, shows almost a monotonic increase of $V$ from the center to the photosphere, whereas the Type–II solutions of 200 and 1000 $M_\odot$ make a deep dip or a loop around $V \sim 2$. The decrease of $V$ toward the dip is caused by a quick decrease in the density outward, which corresponds to a steep rise in the opacity. After the loop, the opacity begins to decrease, which keeps the density at a relatively large value, and then $V$ increases again. Note that such a loop structure is a characteristic property of red giants with hydrogen–shell burning, which has an extended envelope around a dense core (Hayashi et al. 1962).

4. Discussion

Figure 6 shows ZAMS tracks for various chemical composition. The thick and thin curves denote the ZAMS with $X = 0.7$ and $Z = 0.0$, respectively. One additional sequence of $X = 0.35$ and $Z = 0.05$ is also shown for a comparison. Table 1 shows that a hydrogen–deficient star ($X = 0.35, Z = 0.05$) has a higher luminosity and a
lower temperature, compared with that of a hydrogen–rich star \((X = 0.7, Z = 0.05)\) of the same mass. This makes a good contrast to the weak dependence of the luminosity on \(Z\); i.e., the stellar luminosity is almost independent of \(Z\) for a given mass. The difference between helium–rich stars \((X = 0.35)\) and solar composition stars \((X = 0.7)\) in luminosity and temperature is \(\Delta \log L = 0.22\) and \(\Delta T_{\text{eff}} = -0.26\), for 150 \(M_\odot\), and \(\Delta \log L = 0.195\), and \(\Delta T_{\text{eff}} = -0.50\) for 200 \(M_\odot\). In other words, observational information on helium enrichment is important when we derive the stellar masses from the observed luminosities.

We now compare our theoretical ZAMS tracks in the H–R diagram with several very luminous stars which were recently discovered. Figure 6 also depicts the position of several very bright stars \([\log L/(L_\odot) > 6]\) in our Galaxy, the LMC, and the SMC. The distribution of the LMC and the SMC stars (filled symbols) is consistent with our ZAMS curve of \(Z = 0.04\), because Magellanic stars are known to be metal poor. A very massive LMC star, Melnick 42, denoted by the filled circle, has been examined in detail by Pauldrach et al. (1994), who derived the stellar parameter to be \(\log(L/L_\odot) = 6.6\), \(T_{\text{eff}} = \) 50500 K, \(Z = Z_\odot/4\), and \(M/M_\odot = 150\), from model fitting of non–LTE UV spectrum with HST UV spectrum. The position of this star in figure 6 (filled circle) is close to the ZAMS of \(Z = 0.004\) and quite consistent with our aspect. From our sequence of \(X = 0.7\) and \(Z = 0.004\), its mass is estimated to be \(\sim 200 M_\odot\); if the star is helium–rich, the mass is slightly smaller than this value, as mentioned above.

The distribution of these Magellanic Cloud stars seems to be on the whole slightly leftside to that of the galactic stars (open square). This is consistent with the metal deficiency of the Magellanic Clouds stars, although the data number is not sufficient for making any definite statement, and some of which possibly have left the main–sequence to a redward evolutionary excursion.

This figure also shows four massive stars in the galactic center (open triangles). Najarro et al. (1997) have analyzed He I lines of these stars by a non–LTE radiative–transfer method for a pure H–He spherical atmosphere. They showed that all of them are strongly He enriched (He/H > 1). Because these IRS stars are in the galactic center, they are possibly enriched in metal as well. In the H–R diagram, they are located close to our theoretical curve of \(X = 0.35\) and \(Z = 0.05\) in the upper–half part that represents core–halo structure. Therefore, if their interior structure is not far from that of our uniform model, we can expect that their low effective temperature may be attributed to the core–halo structure.

Another candidate for the core–halo structure is the Pistol star. The luminosity and temperature of the Pistol star has been derived by Figer et al. (1998) from a
higher than those of ours (∆ log curves rightward, which is qualitatively in good agree-
ment with a detailed evolutional calculation.

Contents of such stars are useful information as well as a prediction, because we need to distinguish a very young star from an evolved star. Observational estimates of the helium and heavy element content of the convective core, and showed that massive stars (M > 15M☉) leave the main–sequence redward in the H–R diagram, while less massive stars (M < 10M☉) move leftward. Considering the difference in the opacity, i.e., the large peak in the OPAL opacity is not present in the Los Alamos opacity, we can naturally expect that stars of mass > 10M☉ move rightward in the H–R diagram.

The distribution of filled triangles, that denotes stars with hydrogen in the atmosphere, seems to be weighted to the lower temperature side, which is explained by the difference in the opacity. When a helium core–burning star has a hydrogen–rich atmosphere, the star intends to have a more extended radiative envelope due to an increase of the opacity in its surface region.

A few stars locate to the leftside of the curve of Z = 0.02, (e.g., a star at log Teff = 4.95 and log L/L☉ = 6). This may be attributed in part to the difference in the definition of the temperature between ours and Hamann and Koesterke, in which their temperature, depicted here, is defined as that of the bottom of the expanding envelope, where the optical depth is 20. Therefore, the temperature that should be compared with our curve may be slightly smaller than these values. In the presence of a wind mass–loss, however, a rigid definition of
the surface temperature will be very complicated and difficult to compare with ours; such detailed examinations are beyond the scope of the present paper. Within such ambiguities, we therefore conclude that the bending of He ZAMS is consistent with the observed data of WN stars.

5. Conclusions

1. We present the internal structure of chemically homogeneous stars with central nuclear burning. Massive stars develop a core–halo structure ($>100\, M_\odot$ for MS star, and $>15\, M_\odot$ for helium MS star) with a very extended radiative envelope, whereas less massive stars do not. This structure change is caused by the large peak of the OPAL opacity, which is more prominent in more massive metal–rich stars.

2. The upper part of the main–sequence curves redward in the H–R diagram, because the core–halo structure develops well in more massive stars and the surface temperature decreases along with an increase in the stellar mass. The critical mass of main–sequence turning to rightward is $200\, M_\odot$ for $Z = 0.004$, $100\, M_\odot$ for $Z = 0.02$, and $70\, M_\odot$ for $Z = 0.05$ for ZAMS, and $30\, M_\odot$ for $Z = 0.004$, and $15\, M_\odot$ for $Z = 0.02$ for He ZAMS. Because the Population I main–sequence more strongly bends than does Population II, very young massive main–sequence stars are expected to distribute in the order of the metal content in the upper H–R diagram.

3. The distribution of observed very massive stars in the H–R diagram is consistent with our theoretical main–sequences. A ZAMS star of extreme Population I has a very low $T_{\text{eff}}$ despite its young age, which possibly leads to a misclassification as an evolved star. The large radius, owing to the core–halo structure of very young MS star, must be distinguished from the redward excursion from evolutionary effects by observational information on the chemical composition.

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