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The Effects of Stellar Wind, Rotation Velocity, and Overshoot Parameters on The Evolution of Massive Stars using MESA: Case Study of MPG 324, MPG 355, MPG 682

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ABSTRACT

Massive stars (over 8 solar masses) undergo intricate cosmic journeys. Their evolution, shaped by parameters like stellar wind, rotation velocity, and overshoot, generally includes the pre-main sequence, main sequence, and post-main sequence phases. In the post-main sequence, they become supergiant stars, then Wolf-Rayet stars, experience a supernova, and end as neutron stars or black holes. This study models the evolutionary path of massive stars using MESA software, considering stellar wind, rotation velocity, and overshoot. Three stars from the Small Magellanic Cloud galaxy—MPG 324, MPG 355, and MPG 682—are used to represent the mass range described in the Conti Scenario. The model is compared to Conti Scenario and observational data, showing good agreement with luminosity, effective temperature, and evolutionary phase, though not yet at final stages. This provides valuable insights into stellar evolution.

Keywords: stellar evolution, massive stars, MESA Software, stellar wind, rotation, overshoot

INTRODUCTION

In astronomy, stars can be categorized based on their mass. Each of these mass categories has its own evolutionary trajectory, and the evolutionary trajectory of each star varies greatly depending on the physical conditions of the star. This variation is caused by the stellar evolutionary parameters of stellar wind [1], rotational velocity [2-3], overshoot [4], and metallicity [5]. Each parameter has different effects on stellar evolutionary tracks. However, the effect of each parameter is quite difficult to observe individually, and the boundaries of each parameter are still unknown.

One of the most interesting stellar mass categories to study is massive stars. Massive stars are defined as stars with a mass greater than 8 times that of the Sun [6]. The evolutionary tracks of massive stars heavily depend on the evolutionary parameters used. Several studies have been conducted to model the effects of each parameter on the evolution of massive stars, such as metallicity [7], overshoot [8], rotational velocity [9], mass loss [10], and stellar wind [11].

In this study, the evolutionary tracks of three massive stars in the Small Magellanic Cloud (SMC) galaxy will be modeled. The SMC is one of the nearest galaxies to the Milky Way, making it easier to observe and study. By studying a nearby galaxy, a better understanding can be obtained about the variety of stars, clusters, and galaxies. This understanding will help in exploring the physics occurring inside stars, how stars evolve, the influence of stars on their surroundings, how our galaxy was formed and evolved, and, ultimately, gaining deeper insights into the universe.

From the SMC, we selected MPG 324, MPG 355, and MPG 682 as the stars to model. These stars were chosen to represent the mass ranges described in the Conti Scenario from TABLE 1. A combination of three evolutionary parameters—stellar wind, rotational velocity, and overshoot—will be used to obtain the best match with the observational data.

The modeling will be conducted using the stellar evolution code MESA (Modules for Experiments in Stellar Astrophysics), version 23.05.1 [12]. The aim is to model the evolutionary trajectories of MPG 324, MPG 355, and MPG 682 and compare them with observational data. Additionally, this study seeks to understand how these three evolutionary parameters affect the stars' evolutionary trajectories by comparing the results with theoretical models.

Massive Star Evolution

Throughout their lives, massive stars go through three phases of evolution: the pre-main sequence phase, the main sequence phase, and the post-main sequence phase [6].

Pre-Main Sequence

This phase begins when a protostar is formed from the condensation and fragmentation of a molecular cloud. The protostar undergoes gravitational contraction, causing it to shrink, condense, and increase in temperature. The rise in temperature initiates a fusion reaction in its core, marking the evolution of the protostar into a star. The fusion reaction in question is the fusion of hydrogen into helium.

Main Sequence

Fusion reactions in the core of the star generate radiation pressure directed outward toward the star's surface. This radiation pressure increases until it reaches equilibrium with the gravitational contraction pulling inward toward the star's interior. When this equilibrium is achieved, the star enters the main sequence phase, during which hydrogen is burned into helium in its core.

Post-Main Sequence

The fusion reaction inside the core of the star continues until the hydrogen supply is exhausted. Once hydrogen is depleted, the fusion reaction halts. Without fusion reactions to counteract gravitational contraction, the core collapses, and the star's outer envelope expands. At this point, the star leaves the main sequence phase and transitions into the post-main sequence phase.

These evolution phases for massive stars can be described within a general framework known as the Conti Scenario, as outlined in TABLE 1.

TABLE 1. Modified Conti scenario [13]. This scenario describes massive stars' evolution from main sequence phase to post-main sequence phase.

Mass	Evolution phase	
$M > 60\ M_\odot$	O → Of/WNL → LBV → WNL → (WNE) → WC	→ SN Ibc
$M = 40 - 60\ M_\odot$	O → BSG → LBV → WNL → (WNE) → WC	→ SN Ibc
$M = 30 - 40\ M_\odot$	O → BSG → RSG → WNE → WCE	→ SN Ibc
$M = 20 - 30\ M_\odot$	O → (BSG) → RSG → (YSG?)	→ SN II-L/b
$M = 10 - 25\ M_\odot$	O → RSG → (Cepheid loop, $M < 15\ M_\odot$) → BSG	→ SN II-P

Stellar Evolution Parameters

Several stellar evolution parameters may influence how a star evolves over time. Each parameter has its own effect on the stellar evolution phases. These parameters vary for each star, as the physical conditions of stars are unique.

Stellar Wind

Stellar wind typically occurs during the post-main sequence phase and is more noticeable in stars with larger masses. During the red supergiant phase, if the stellar wind is strong enough, it can shed the star's envelope—especially the H-envelope.

Mass Loss

Mass loss is closely related to stellar wind. It can result in a significant reduction in the mass of the convective core and the luminosity of the star. Mass loss can prolong the time stars spend in the main sequence phase, alter supernova precursors, and affect overall evolutionary stability.

Rotational Velocity

A star can rotate very rapidly or very slowly. Rotational velocity influences the duration of the main sequence phase, as it often aids the 'dredge-up' process in the star.

Metallicity

Metallicity quantifies the mass proportion of chemical elements other than hydrogen and helium (H and He) in the star. It affects the compactness, temperature, and mass loss of the star. Generally, higher metallicity results in a less compact star with a lower temperature, influencing mass loss and indirectly affecting the star during the main sequence phase.

Overshoot

Overshoot occurs when convective cells inside the star are propelled into the radiative layer. This process plays a significant role in the 'dredge-up' process, bringing lighter elements from the surface to the core and enabling the continuation of fusion reactions. Consequently, overshoot affects the duration of the star's main sequence phase.

METHOD

MESA Software (version 23.05.1) is used for modeling stellar evolution [10-12]. The software needs to be initialized on a Linux operating system, and additional required resources must be downloaded. After MESA is initialized and confirmed to be functioning properly, the *mesa-r23.05.1/star/work* directory can be accessed. This directory contains all the necessary codes and inlists for creating a single star evolutionary model.

Within this directory, the parameters for the model are set in the *inlist_pgstar* and *inlist_project* files. The *inlist_pgstar* file includes adjustments for the output files, particularly for generating pictures and movies. The *inlist_project* file contains parameters that can be modified to shape the model. After the parameters are configured, MESA is run. In this research, only the *inlist_project* file was modified to adjust the required parameters.

After all the running processes are completed, the output files are stored in the */LOGS* folder within the same directory. Typically, the outputs include *profile.data*, which contains all of the profiles generated in the model; *profile.index*, which lists all of the profiles; *pgstar.dat*, which describes each of the output columns; and *history.data*, which summarizes all of the models generated by MESA. For this research, only the *history.data* file was used.

All the MESA output files consist of numerical data, including mass, luminosity, effective temperature, and other parameters related to the stellar interior model. To visualize and analyze the data, the Python programming language is used. For this research, the data needs to be visualized as a Hertzsprung-Russell diagram (HRD), which is a diagram showing a star's evolutionary trajectory from the pre-main sequence phase to the post-main sequence phase. The HRD is obtained by plotting the effective temperature and luminosity data in historical order. All these steps are repeated for each set of star parameters listed in TABLE 2 below. The luminosity and effective temperature from observational data are also plotted to compare with the evolutionary trajectories.

In this research, the evolutionary trajectories of MPG 324, MPG 355, and MPG 682 are modeled using parameters obtained from [14]. MPG 324, MPG 355, and MPG 682 are members of the SMC, with a metallicity of approximately 0.004 (0.2 times the solar metallicity) [15]. These parameters, listed in TABLE 2, are inputted into MESA's inlists.

TABLE 2. Fundamental stellar parameters. Column 2-6 obtained from [14].

Stars	Spectral type	Evolution mass ($M_\odot$)	Rotational velocity (km/s)	$\log\left(\frac{L}{L_\odot}\right)$	Effective temperature (kK)	Overshoot
MPG 324	O4V	$40.0^{+3.2}_{-3.0}$	300	5.51	42.1	0.02 – 0.035
MPG 355	ON2III(f*)	> 70	400	6.04	51.7	0.02 – 0.065
MPG 682	O9V	$20.8^{+1.5}_{-1.7}$	< 300	4.89	34.8	0.015 – 0.03

TABLE 3. Input of MESA in '*inlist_project*'

Parameters	MPG 324	MPG 355	MPG 682	Reference
New_surface_rotation_v	300	400	100, 150, 200, 250	[14]
Initial_mass	40, 40.4	70, 80, 85, 87	20.8, 21.4	[14]
Initial_z		0.004		[15]
Overshoot_scheme		Step		[16]
Overshoot_zone_type		Any		[16]
Overshoot_zone_loc		Any		[16]
Overshoot_bdy_loc		Any		[16]
Overshoot_f	0.02, 0.035	0.02, 0.045, 0.065	0.015, 0.02, 0.03	-
Overshoot_f0		0.0005		[17]
Mixing_length_alpha		1.6		[18]
Cool_wind_RGB_scheme		Nieuwenhuijzen		[16]
Cool_wind_AGB_scheme		Nieuwenhuijzen		[16]
Default_net_name		Approx21_cr60_plus_co56.net		[16]
Zbase		0.004		[15]

Several runs are conducted using the overshoot ranges to obtain the best fit with the observational data. In TABLE 3, the parameters included in MESA's inlists are described, specifically for the *inlist_project* file. Several values adjusted during the modeling process are also included.

RESULTS AND DISCUSSION

After MESA is run for each parameter variation, the best evolutionary trajectories for each star in the HRD are obtained. These evolutionary trajectories, shown in FIGURE 1, are derived from the *history.data* file in MESA's output, where the *log_L* and *log_Teff* columns are used to plot the HRD. These trajectories exhibit the best fit with the observational data, which is labeled with a red star in each plot. The trajectories begin at the pre-main sequence phase, progress through the main sequence phase, and end in the red sequence phase.

From the plot, the main sequence phase is observed to start at the upper-left side of the trajectory, where it rises before turning back toward the right side of the overall plot. The red sequence phase is characterized by high luminosity but lower temperature.

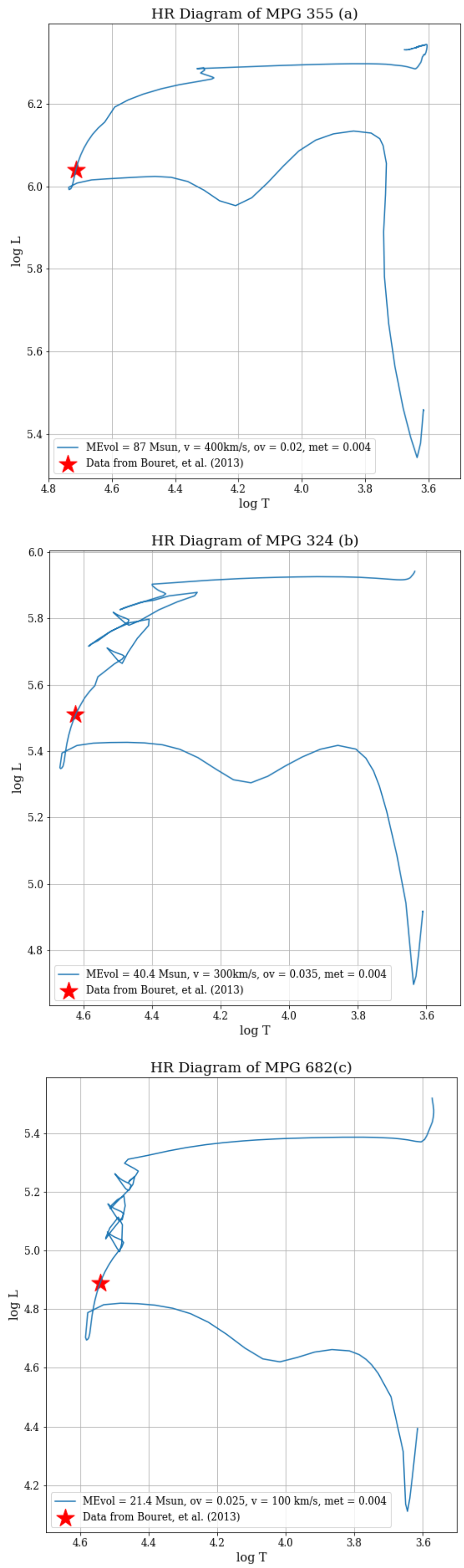

FIGURE 1. Evolutionary trajectory models for: (a) MPG 355, (b) MPG 324, (c) MPG 682.

TABLE 4. Stellar evolution parameters obtained from modelling, for each star.

Stars	Phase of Evolution	Evolution mass ($M_\odot$)	Rotational velocity (km/s)	Metallicity	Overshoot
MPG 324	MS	40.4	300	0.004	0.035
MPG 355	MS	87.0	400	0.004	0.020
MPG 682	MS	21.4	100	0.004	0.025

These evolutionary trajectories are obtained using the parameters listed in TABLE 4. The position of each star in the HRD is determined using luminosity and effective temperature data from [14]. Each star's position on the HRD plot is marked as a red star. It is shown that the evolutionary tracks obtained from the modeling align well with these positions. This HRD closely resembles the one presented in [19] and is in good agreement with the HRD model of rotating massive stars shown in [20] and [21]. Based on the evolutionary parameters used, it is demonstrated that the combination of rotational velocity and overshoot extends the duration of a star's main sequence phase. This conclusion is drawn by comparing the length of the main sequence phase in the model with the HRD model of rotating massive stars in [20].

From the evolutionary trajectories, it is shown that MPG 324, MPG 355, and MPG 682 remain in their main sequence phase. For MPG 324 and MPG 682, this finding aligns well with the observational data, as these stars are categorized as V-class stars in their spectral types (TABLE 2), indicating that they are in the main sequence phase. However, for MPG 355, the evolutionary phase obtained from the model does not align well with the observational data. This star is categorized as a III-class star in its spectral type (TABLE 2), which indicates that it should be in the giant phase (counted as post-main sequence) rather than the main sequence phase.

However, the HRD model in FIGURE 1 has not yet reached the final stage of the stars' evolution, as described in the Conti Scenario (TABLE 1). For more accurate results compared to the observational data, further adjustments to the parameters are required, particularly for the evolutionary parameters not included in the current modeling.

CONCLUSION

Using a combination of evolutionary parameters—namely overshoot, rotational velocity, and metallicity—the evolutionary tracks for the stars MPG 324, MPG 355, and MPG 682 were modeled using MESA. All models began at the pre-main sequence phase, progressed through the main sequence phase, and concluded at the red supergiant phase. Unstable trajectories were observed at the end of the main sequence phase, which may have been caused by insufficient parameter adjustments. However, the effects of overshoot and rotational velocity were evident from the length of the main sequence phase in the model.

A slight adjustment to the stellar mass within the error range calculated by [14] was made to achieve a better fit between the model and the observational data. A specific value from the overshoot range listed in TABLE 2 was used to refine the mass value of the stars. A good fit was achieved between the HRD in FIGURE 1 and references such as [19], [20], and [21], using the parameters listed in TABLE 4. The model also indicated that MPG 324 and MPG

682 remain in their main sequence phase, consistent with the fundamental stellar parameters in [14] derived from observational data. However, a significant discrepancy was identified in the evolutionary phase of MPG 355. While the model determined that MPG 355 is still in the main sequence phase, observational data from [14] suggest that MPG 355 is in the giant/post-main sequence phase.

It was noted that the model has not yet reached the final stage of stellar evolution. To produce a complete evolutionary track for each star, as described in the Conti Scenario, additional evolutionary parameters, such as radiation-driven stellar wind and convective boundary mixing, are required [21]. The parameters obtained also need to be recalibrated for other stars in the SMC, particularly for stars from other galaxies with different characteristics.

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