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Is There a Critical Metallicity of Mass Loss in Massive Star Evolution?

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Abstract

Stellar winds play an important role in stellar feedback by injecting mass and energy into the interstellar medium. Mass loss of progenitor stars also affects their supernova types. However, the amount of mass lost and energy released during stellar evolution are highly uncertain. Especially, for low-metallicity stars in the early and local universe, while mass loss is previously thought to be weak, its role is still unknown. To investigate mass loss of massive stars quantitatively, we perform 1D stellar evolution simulations with MESA code by including wind recipes based on empirical laws. We generate a grid of models with different initial masses and metallcities, and systematically study their effects on mass loss. Our results suggest a critical metallicity $Z_c \sim 0.001$ marked as a dramatic transition of mass loss. At $Z < 0.001$ regime, very little fractions of stellar masses are lost. When $Z > 0.001$, the fractions of mass lost become large, and remain similar at different $Z > Z_c$. The red supergiant phase is key to drive mass loss. Nevertheless, the exact critical Z_c for stars of different masses is not well defined. Furthermore, we calculate the kinetic energy released by stellar winds. The mass loss histories from our 1D MESA models can provide realistic initial conditions for the forthcoming 2D and 3D simulations of stellar winds.

1 Introduction

Mass loss of massive stars via stellar winds is an important component of stellar feedback. It forms CSM, injects energy/momentum into the interstellar medium (ISM), and also affect the final type of supernovae (SNe) when massive stars die.

To understand the stellar feedback in the early universe, we need to study mass loss of low-metallicity massive stars. However, the relationship between mass loss and metallicity is uncertain. To obtain a more complete picture, we aim to quantify the stellar mass loss as a function of initial mass and metallicity.

2 Methods

We use the Modules for Experiments in Stellar Astrophysics (`MESA`; Paxton et al., 2011, 2013, 2015, 2018, 2019) to perform 1D stellar evolution simulations with mass loss. To model mass loss, Vink's hot wind recipe (Vink et al., 2000, 2001), de Jager's cool wind recipe (de Jager et al., 1988), and Nugis' Wolf-Rayet (WR) wind recipe (Nugis & Lamers, 2000) are included in our `MESA` models. The mass loss rates are functions of the stellar properties, such as effective temperature, luminosity, and metallicity.

3 Total Mass Lost During the Stellar Lifetime

By integrating mass lost for each timestep during the stellar lifetime, the total mass lost is obtained. The total mass lost does not smoothly increase with metallicity. Instead, there seems to be a critical metallicity at $Z_c \sim 10^{-3}$. Below the critical metallicity, the amount of mass lost is very low. Above the critical metallicity, there is a significant amount of mass lost, but the amount does not largely increase with metallicity $> Z_c$, that is not a well-defined value for stars of different masses.

4 What is the Origin of the Critical Metallicity?

There seems to be a dichotomy in the behavior of mass loss. We examined the evolution of various physical parameters, and found that the stars with high mass lost are actually red supergiants (RSGs) formed after core helium burning starts, while those with nearly no mass lost never becomes RSGs.

Here is the relation between metallicity and mass loss: a low-metallicity star can never evolve to a RSG, so the cool wind scheme is never on, and thus it has very low mass lost. In contrast, a high-metallicity star are likely to form a RSG after core helium burning starts, and then it has high mass lost. Whether a star becoming a RSG largely determines the total mass lost. Nevertheless, why the low-metallicity stars can never evolve to RSGs is still a remaining question.

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