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Evolution of Massive Population III Stars

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Abstract

While the evolution of massive stars in the local Universe is dominated by mass-loss, the evolution of massive Population III stars should be dominated by rotation. An important effect of rotation is rotationally-induced chemical mixing that can dramatically change the stellar structure and the nucleosynthesis. This has significant consequences in the predicted explosion types of Population III stars.

Keywords: stars: evolution - stars: rotation - stars: population III - supernovae - Gamma-ray bursts.

1 Introduction

Formation of Population III (Pop III) stars marks the end of the so-called dark age in the early Universe. These first stars are believed to be intrinsically massive (30 $M_\odot < M < 1000\ M_\odot$), given that the primordial gas does not contain any efficient coolants in star-forming regions, and supposed to play a key role in the evolution of the early Universe, in many aspects (see Bromm 2013, for a recent review). Neutral hydrogens and heliums are re-ionized by the first lights from these first generations of stars, and the primordial gas becomes polluted with heavy elements produced by both hydrostatic and explosive nucleosyntheses in them. Although direct identification of them will be highly unlikely even with next generations of telescopes, their nature can be indirectly probed with observations of their explosions that may be luminous enough to be discovered in near future. Observational studies on the surface abundances of extremely metal poor stars, which are believed to retain the nucleosynthesis signatures of Pop III stars, will also provide a good constraint on the evolution of Pop III stars.

Theoretical predictions that can confront future observations are indispensable for these efforts (e.g., Marigo et al. 2001; Heger & Woosley 2002; Umeda & Nomoto 2003; Heger & Woosley 2010; Kasen et al. 2011; Limongi & Chieffi 2012; Dessart et al. 2013; Whalen et al. 2013; Tanaka et al. 2013). In this paper, I discuss the current understandings on the evolution of massive Pop III stars, focusing on the role of rotation in the stellar evolution (e.g., Marigo et al. 2003; Ekström et al. 2008; Yoon et al. 2012). Recent numerical studies indicate that massive Pop III stars would be born with surface rotation close to the critical value (e.g., Stacy et al. 2011).

2 Importance of Rotation

In our Galaxy, stars having masses higher than about 30 $M_\odot$ usually undergo strong mass-loss during their evolution. This is because numerous metal lines in their atmospheres and the consequent high radiation pressure cause instabilities of various sorts at the stellar surfaces (see Puls et al. 2008, for a recent review). The evolution of massive stars at high metallicity is therefore dominated by mass-loss. For instance, in the local Universe, stars as massive as 120 $M_\odot$ at their birth would lose more than 100 $M_\odot$ throughout their lives, dying as 10 - 20 $M_\odot$ stars (e.g., Meynet & Maeder 2005). This also means that such massive stars would rapidly lose most of their initial angular momentum, rendering the effect of rotation minor or negligible in general.

By contrast, it is believed that massive Pop III stars do not experience significant mass-loss because they are generally very stable (Baraffe et al. 2001). In addition, lines by hydrogen and helium are too weak to drive radiation-driven winds (Krticka & Kubát, 2006). Therefore, massive Pop III stars would retain a significant fraction of the initial angular momentum throughout their evolution. This has the following important consequence: while the evolution of very massive stars at high metallicity is dominated by mass-loss, the evolution of massive Pop III stars is dominated by rotation.

An important effect of rotation is chemical mixing resulting from rotationally-induced hydrodynamic instabilities like Eddington-Sweet circulations that are driven by thermal imbalance inside rapidly rotating stars (e.g., Maeder 2009). See Brott et al. (2011b) for a

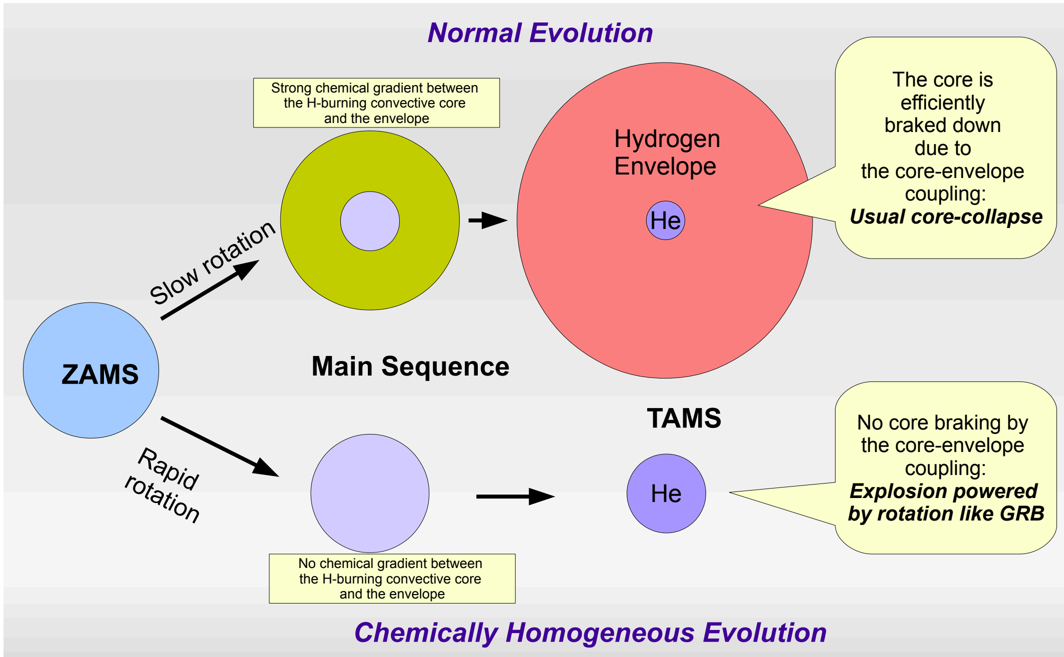

Figure 1: Illustration for the bifurcation of massive star evolution according to their initial rotational velocity. Slowly rotating massive stars develop the classical core-envelope structure such that they become red-supergiant stars during the post-main sequence phases. Rapidly rotating massive stars, on the other hand, may undergo very rapid rotationally-induced chemical mixing to such an extent that quasi-chemical homogeneity can be maintained on the main sequence, if their initial metallicity is sufficiently low. In this case, stars are gradually transformed into helium stars at the end of the main sequence. See Yoon & Langer (2005), Yoon et al. (2006), and Woosley & Heger (2006) for more details.

recent dicussion on the observational tests and related uncertainties of the rotational mixing scenario. The hydrogen burning core is supplied with fresh hydrogen-rich material from the envelope because of this mixing, resulting in a larger core size than in the corresponding case without rotation. The most extreme case is the so-called chemically homogeneous evolution (CHE), which is illustrated in Fig. 2. With a sufficiently high rotational velocity (i.e., more than about 50% of the local Keplerian value at the equatorial surface), the chemical mixing timescale by Eddington-Sweet circulations can be shorter than the nuclear burning time of hydrogen, so as to maintain quasi-chemical homogeneity in the star. Because almost all the hydrogens in the star participate nuclear burning in this way, the star gradually becomes a massive helium star at the end of the main sequence. This is an important evolutionary channel to make massive He stars at low metallicity, while CHE may not play an important role at high metallicity because of rapid angular momentum loss via stellar winds (see Yoon et al. 2006). This mode of evolution is also considered an important channel to produce long gamma-ray bursts from metal-poor massive stars (Yoon & Langer 2005; Yoon et al. 2006; Woosley & Heger 2006).

Stars with the CHE evolve bluewards instead of evolving redwards on the HR diagram. The presence of such stars in the early Universe would make significant impact on the history of reionization, because they produce more ionizing photons by several factors than stars that follow the normal evolution (Yoon et al. 2012). This particular mode of stellar evolution also results in a significant diversity of Pop III star explosions, as discussed below.

3 Explosions of Massive Population III Stars

The theoretical predictions on the final fates of massive Pop III stars are given as the phase diagram in Fig. 2. Pop III stars that develop the classical core-envelope structure would die as red or blue supergiant stars, and their final fates may not be much different from those

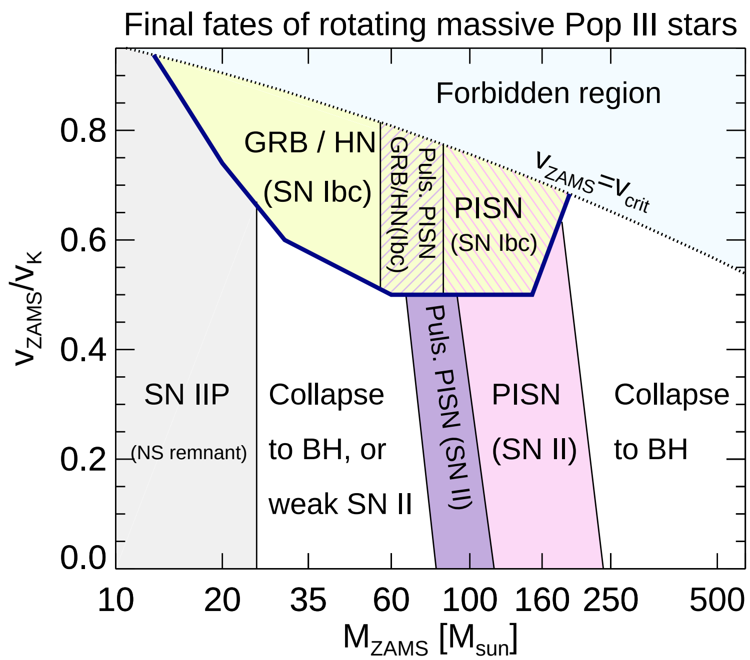

Figure 2: Final fates of massive Pop III stars for given initial masses and rotational velocities, predicted from the stellar evolution models by Yoon et al. (2012). The rotational velocity on the zero-age main sequence is given in units of the Keplerian value at the equatorial surface (i.e., $V_{\rm K} = \sqrt{GM/R}$). We adopted the most up-to-date calibration for the rotationally-induced chemical mixing efficiency by Brott et al. (2011a). The region for the chemically homogeneous evolution (CHE) is marked by yellow color, and the thick solid line gives the boundary between the CHE regime and the region for the normal evolution. Different regions are marked by expected final outcomes: type II supernovae (SN II), collapse to black hole (BH), pulsational pair-instability supernovae (Puls-PISN), pair-instability supernovae (PISN), long gamma-ray bursts (GRB), hyper-novae (HN), Type Ib or Ic supernovae (SN Ibc). In the forbidden region, the equatorial surface velocity exceeds the critical velocity: $V_{\rm crit} = \sqrt{(GM/R)[1-\Gamma]}$, where Γ is the Eddington factor at the stellar surface. This figure is taken from Yoon et al. (2012).

of non-rotating Pop III stars as predicted by Heger & Woosely (2002). But the limits of the initial masses for pulsational pair-instability and pair instability supernovae would move downwards for a higher initial rotational velocity, because rotational mixing tends to increase the He core masses.

As explained above, in the CHE regime, Pop III stars would die as massive helium stars and therefore produce supernovae of Type Ib/c. Conditions for long gamma-ray bursts can also be fulfilled in this regime for an initial mass range of 13 - 84 $M_\odot$. While non-rotating Pop III stars would require initial masses of about 140 - 270 $M_\odot$ to produce a pair instability supernova, this mass range would decrease to about 84 - 190 $M_\odot$ in the CHE regime (see also Chatzopoulos & Wheeler 2012). Another interesting prediction is that for intial masses of about 56 - 84 $M_\odot$, a pulsational pair-instability supernova would be followed by a long gamma-ray bursts, only several years later. Given that gamma-ray jets would interact with a very massive circumstellar matter in this case, extremely bright afterglow might be produced. Our models also predict that the final masses of Pop III GRB progenitors ($\sim 10-70$ $M_\odot$) would be significantly more massive than those of GRB progenitors in the local Universe ($\sim 10-20$ $M_\odot$; Yoon et al. 2006).

On the other hand, recently several authors argued for super-collapsar formation in very massive Pop III stars ($M > 270$ $M_\odot$; Mészáros & Rees 2010; Komissarov & Barkov 2010; Suwa & Ioka 2011). However, our models show that very massive Pop III stars with initial masses larger than about 190 $M_\odot$ cannot retain enough angular momentum in the core to produce any rotation-powered event at their deaths. This is because such stars have a very large convective core that leads to efficient angular momentum transport from the innermost layers to the stellar surface, and because large Eddington-factors of these stars facilitates mass and angular momentum loss via centrifugally driven mass-shedding.

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DISCUSSION

DOROTA ROSINSKA: You have shown that evolution of low-metallicity massive stars strongly depends on rotation. Such stars should rotate differentially. What laws of differential rotation you assume? How results depend on the degree of differential rotation (Ω_e/Ω_c; Ω_e is the angular velocity at the equatorial surface, and Ω_c the angular velocity at the center)?

SUNG-CHUL YOON: Stars always tend to rotate differentially because of the contraction of the core that results in spinning-up the central layers. The degree of differential rotation in a star is then determined by the efficiency of the angular momentum transport from the core to the envelope. I.e., we do not "assume" the degree of differential rotation, but it is self-consistently calculated with a given prescription for the transport of angular momentum. In our models, we adopted the so-called Talyer-Spruit dynamo (Spruit 2002) which leads to a very strong coupling between the core and the envelope, making a star rotate almost rigidly on the main sequence. Stellar evolution models including the Tayler-Spruit dynamo have proved to be consistent with observations, in terms of the predicted spin-rates of stellar remnants like white dwarfs and neutron stars (Suijs et al. 2008).

MATTEO GUAINAZZI: Which black hole spin distribution would you expect from your evolutionary scenario?

SUNG-CHUL YOON: Bimodal distribution. If a BH forms in the CHE regime, its Kerr parameter will be close to 1. Otherwise, BHs will not have any significant angular momentum, having a Kerr parameter close to zero.