The Final Fate of Supermassive $M \sim 5 * 10^4\ M_\odot$ Pop III Stars: Explosion or Collapse?

C. Nagele[1], H. Umeda[1], K. Takahashi[2], T. Yoshida[1], K. Sumiyoshi[3]; [1]Univ. Of Tokyo, [2]Max Planck Institute, [3]Numazu College of Technology

■We investigate the possibility of a supernova in supermassive population three stars induced by a general relativistic instability occurring in the helium burning phase. These explosions could occur via rapid helium burning during an early contraction of the isentropic core. Such an explosion would be visible to future telescopes and would disrupt the proposed direct collapse formation channel for early universe supermassive black holes. We simulate first the stellar evolution from hydrogen burning using a 1D stellar evolution code with a post Newtonian approximation; at the point of dynamical collapse, we switch to a 1D general relativistic hydrodynamics code with the Misner-Sharpe metric. In opposition to a previous study, we do not find an explosion in the non rotating case, although our model is close to exploding for a similar mass to the explosion in the previous study. When we include slow rotation, we find one exploding model, and we conclude that there likely exist additional exploding models, though they are probably rare.

Introduction

Supermassive black holes have been found in the early universe around redshift 6-7. One of the proposed formation mechanisms is the direct collapse scenario, whereby a supermassive Pop III star leaves an intermediate mass BH seed. We investigate whether these stars actually collapse to black holes, or instead explode via a general relativistic explosion.

Method

■First, we calculate the evolution of the massive stars from H burning using a stellar evolution code. This code includes the first order post newtonian TOV corrections. This inclusion is necessary to accurately simulate the evolution of stars with more than 1000 solar masses. However, because this code lacks both a full GR treatment and an acceleration term, we switch to a GR hydrodynamics code after the onset of dynamical collapse. Then the star either 'explodes' due to rapid helium burning or collapses to a black hole. This is the main result we are interested in because it has implications of the viability of the direct collapse scenario.

Dynamical collapse occurs during the helium burning phase in the mass range we consider. First the GR instability condition (Chandrasekhar) is fulfilled

$$\rho_{\mathrm{crit}} = 1.994 * 10^{18} (\frac{.5}{\mu})^3 (\frac{M}{M_\odot})^{-7/2} \ \mathrm{g\ cm^{-3}}$$

causing the star to contract and central helium burning to increase. Then, after about 10^{12} seconds, the star enters adiabatic collapse. Our criterion for switching between codes involves the timestep of the stellar evolution code becoming smaller than the KH timescale of the star.

Collapse or Explosion?

■Before testing realistic models, we would like to know what the condition is for an explosion. That is, we would like to be able to predict from the stellar evolution calculation which type of models will explode and collapse. In practice this is tough to do, but we can get a rough idea by looking at the amount of helium present in the star when the switch between codes is made.

Example Models

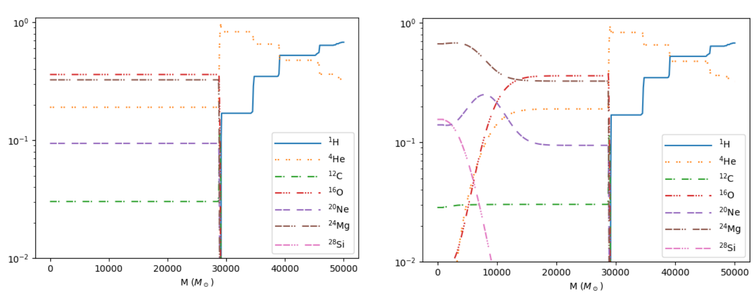
Collapse $M = 5.5 \times 10^4\ M_\odot,\ \log\Omega = -15$ Explosion $M = 5 \times 10^4\ M_\odot,\ \log\Omega = -10.4$

Explosion Mechanism

■This explosion is powered by triple alpha and oxygen alpha capture reactions that occur on a long timescale (~10000 s). As the star collapses, if enough helium is present, the star stabilizes against collapse and then eventually expands at ~2 times the escape velocity.

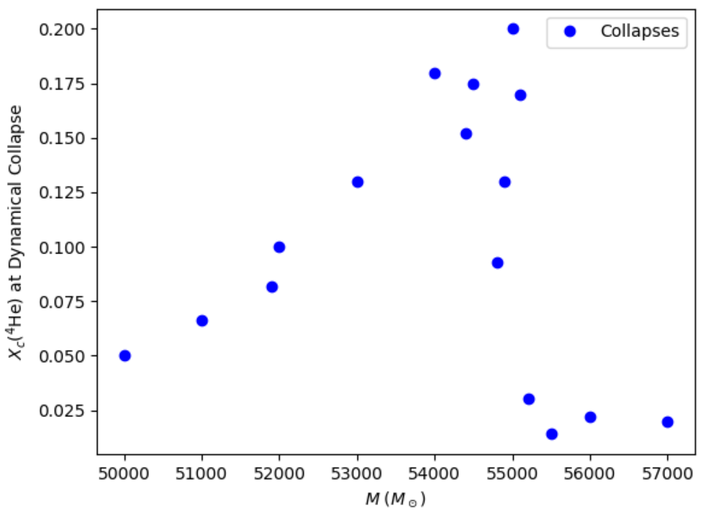
Isotope	^{1}H	^{4}He	^{12}C	^{16}O	^{20}Ne	^{24}Mg	^{28}Si	Total
$M_{\mathrm{init}}\ (M_\odot)$	8780	17872	897	10400	2706	9341	6	50002
$M_{\mathrm{final}}\ (M_\odot)$	8775	16329	891	7044	3963	12185	812	50002
$\Delta M\ (M_\odot)$	-5	-1543	-6	-3355	1257	2845	806	0

This table shows the amount of material burnt in the example explosion (previous section). Below, are the initial and final (respectively) chemical distributions.



No Rotation: No Explosion

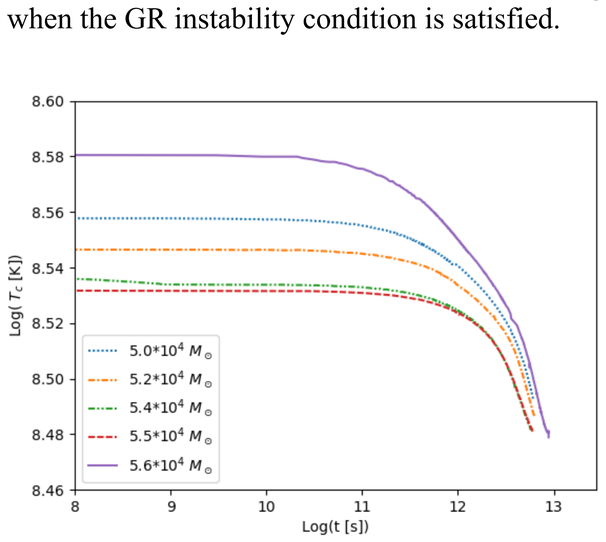
■Models with log Ω < -15 are considered non rotating. For the non rotating case, we focused on the below mass range because of an explosion discovered by Chen et al. for M = 55500 Msun. We do not find any explosions in this mass range for the non rotating case. We do find a peak in the central helium abundance.



■The peak occurs at at M = 55000 solar masses, near where the previous explosion was found. The gradual decrease in helium at lower mass is due to the GR instability condition not being satisfied until later times.

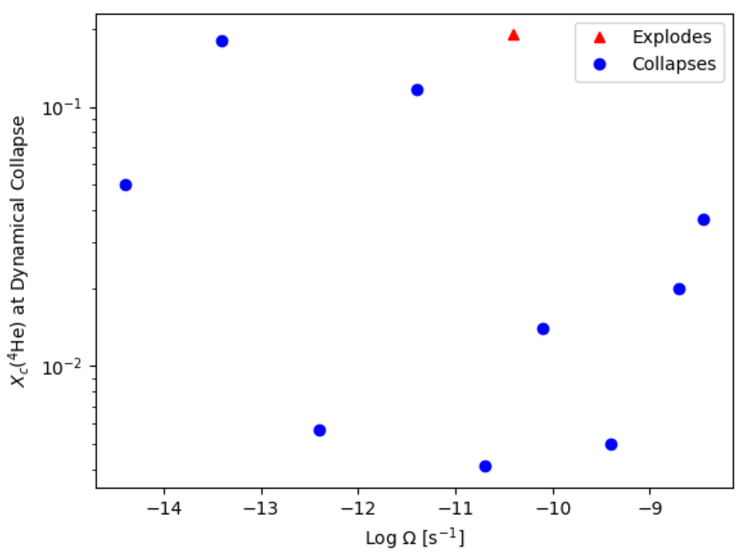
$$\mathrm{M} \downarrow \overset{GR}{\Rightarrow} \rho \uparrow \Rightarrow \mathrm{T} \uparrow \Rightarrow\ ^4\mathrm{He} \downarrow$$

■The sharp decrease at higher mass is due to the GR instability condition being fulfilled during H burning. If this is the case, the star contracts much more quickly because of a lack of helium burning to support the star. The star quickly contracts to high T and stabilizes briefly, during which time it burns all of its helium. Both trends can be seen below. The curves begin (on the right) when the GR instability condition is satisfied.

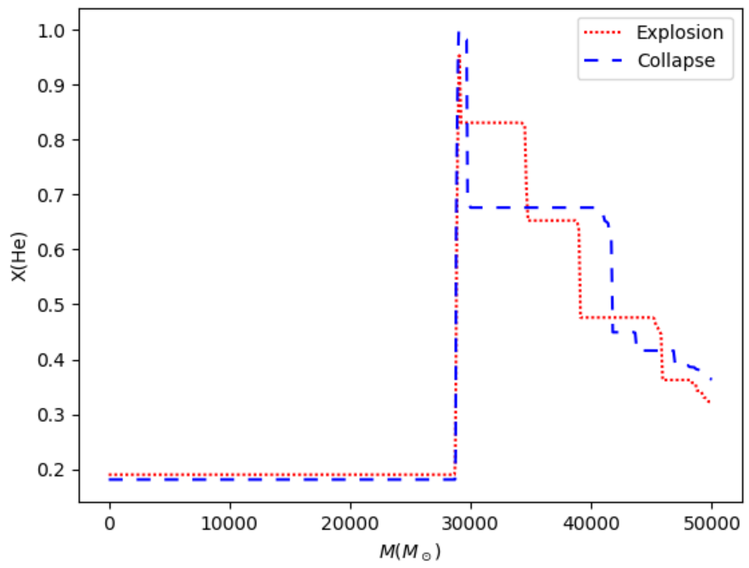


Rotation: One Explosion

■The stellar evolution code is able to include rotation, so we calculated several models to see if there would be any effect. The results did not display any clear trend, but we did find one explosion for M = 5 x 10^4 solar masses (below).



■This distribution is likely caused by the stochastic nature of the envelope. If the helium shell of the envelope is very heavy, it causes the effective weight of the core to increase. A heavier core can cause an earlier collapse, leading to an explosion.



Conclusions

■Although we only found one explosion, we think that others exist with the right combination of mass, rotation, and envelope structure. However, they are likely quite rare. Thus, searching for these explosions in the early universe could be a good test of the DCBH hypothesis, because the explosions would be present, but not plentiful enough to disrupt the formation channel.

References

■Chen, Heger, Woosley, Almgren, Whalen, Johnson, 2014, APJ.
■Chandrasekhar, 1964, ApJ.