Modelling Primordial Supermassive Stars in MESA

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ABSTRACT
The number of high-redshift quasars are ever growing, which implies that our current models of how these quasars from are inconsistent with these observations. This article explores and reasons for a different model for the formation of the first quasars. This article is supporting current models and theory from Haemmerlé et al. (2018a) and Surace et al. (2019) which are the basis for the models created in this article, wherein we model a supermassive star of zero metallicity forming in an atomically cooling halo with an accretion rate of 1 $M_\odot$ yr^{-1} reaching $10^5 M_\odot$ before a direct collapse black hole (DCBH). We also aim to investigate the relativistic terms used in MESA compared to that of KEPLER. We find evidence that Primordial Supermassive Stars are bright, "A" class stars, that stay within the Hayashi limit for the majority of their lifetime.

Key words: quasars: general – quasars: supermassive black hole, early universe — dark ages, reionization, first stars — galaxies: high-redshift

1 INTRODUCTION

In recent years high-redshift quasars have been discovered with more then three hundred being at redshift z ≥ 6 (Fan et al. 2006; Willott et al. 2009; Mortlock et al. 2009) and seven at redshift z ≥ 7 (Mortlock et al. 2011; Bañados et al. 2018). This means that these quasars formed at least 690 Myrs after the big bang and dates the oldest quasars discovered at ≈ 13.1 Gyrs old. Current leading theory suggests that these supermassive stars (SMSs) are Pop. III stars in hot, atomically cooling halos formed at redshifts $15 \geq z \geq 20$ and are the progenitors for supermassive black holes (SMBHs), or quasars (Haemmerlé et al. 2018a).

There are various models for the formation and evolution of primordial SMSs; whether it be through unusually strong Lyman-Werer UV fluxes (Latif et al. 2014b; Agarwal et al. 2016; Wise et al. 2019); highly supersonic baryon streaming motions (Latif et al. 2014a; Hirano et al. 2017; Schauer et al. 2017); or self-annihilation of dark matter (Spolyar et al. 2008; Freese et al. 2008). The former models can suppress star formation in a massive halo until it reaches $\approx 10^7 M_\odot$ and virial temperatures of $\approx 10^4$K, which causes rapid atomic cooling and later catastrophic baryon collapse. This would SMSs to grow at rates $\leq 1 M_\odot$ yr^{-1} (Lodato & Natarajan 2006; Latif & Volonteri 2015). Additionally, due to a general relativistic instability (Chen et al. 2014), most of these stars would die in the form of a DCBH.

Pop III SMSs are the lead candidates for the seeds of the DCBHs, however this is not the case for smaller Pop III Primordial stars due to harsh conditions for rapid growth (Whalen et al. 2004, 2012).

Most simulations suggest that these rapidly accreting stars are red, cool, hypergiants (Woods et al. 2017; Haemmerlé et al. 2018a; Haemmerlé et al. 2018b). Spectra simulations suggest however that they are hot, blue, supermassive stars which has been investigated using TLUSTY and CLOUDY in Surace et al. (2019).

The DCBHs formed from these stars theoretically have the capability to reach super- and even hyper-Eddington growth (Volonteri et al. 2015), and is evident from recent simulations of accretion rates in the formation of SMSs.

Due to the composition of the Universe at these early redshifts (that being 76% hydrogen and 26% helium), the conditions under which the halos formed, and the sheer masses of these SMSs, the composition and physics of these stars are different to that of today's stars.

Primordial SMSs were composed of almost entirely Hydrogen and Helium, with trace amounts of lighter metals - predominantly Lithium - and therefore be of negligible metallicity. Additionally, they had a relatively low Helium mass fraction in accordance with the chemical composition of the universe. Data of which Peimbert (2008) analysed and concluded with a value of 0.2477 ± 0.0029 [1].

[1] observed value

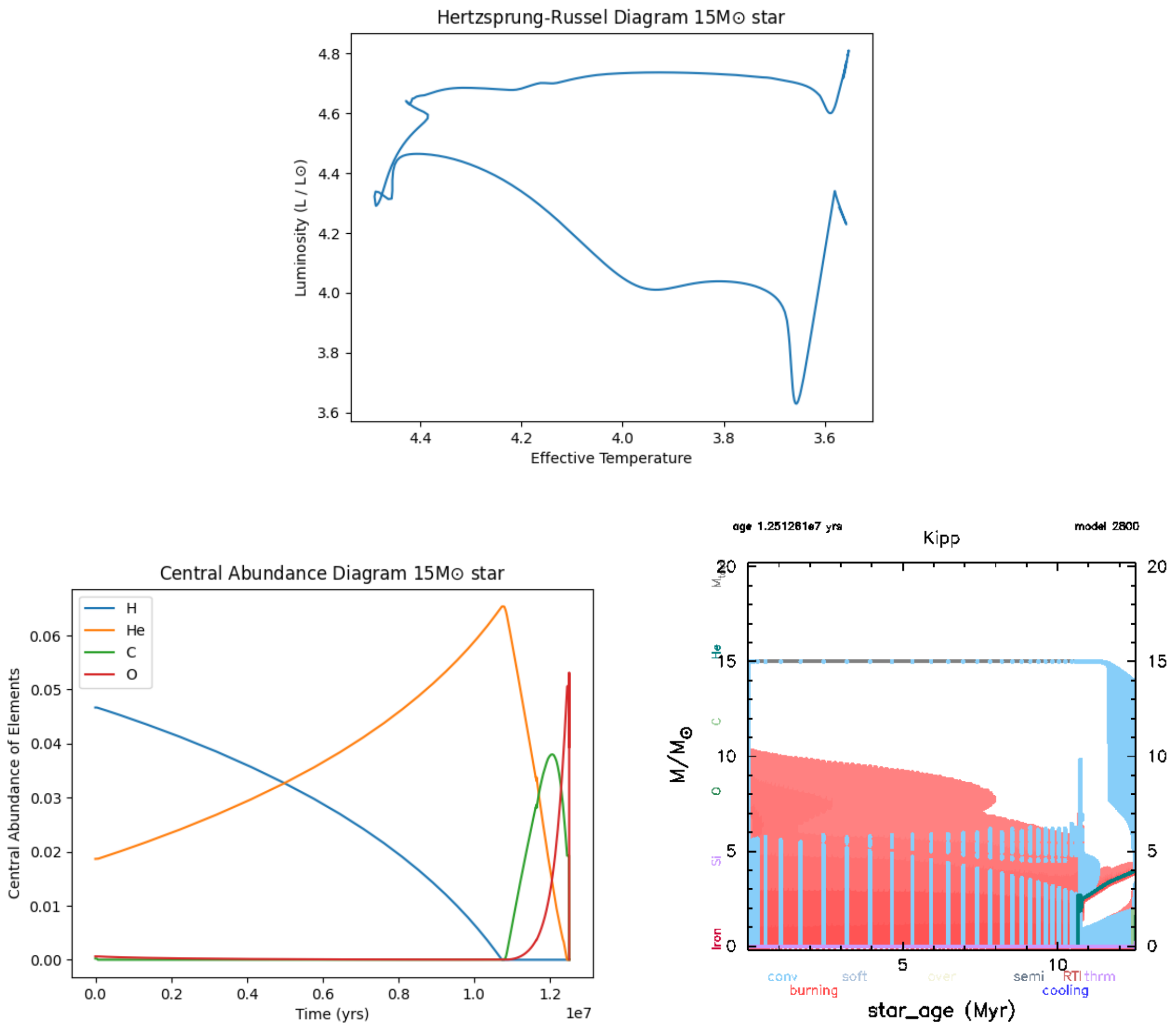

Figure 1. Top: A Hertzsprung Russel diagram depicting the pre-main sequence through to the post-main sequence of a $15M_{\odot}$ star in MESA. Bottom-Left: An abundance diagram analysing the pre-main sequence through to the post-main sequence of a $15M_{\odot}$ star in MESA. Bottom-Right: A Kippenhahn diagram analysing the pre-main sequence through to the post-main sequence of a $15M_{\odot}$ star in MESA. It shows mixing and convection regions (*blue*), burning regions (*red*), and radiative zones (*white*).

Abbreviation	Description
ZAMS	Zero Age Main Sequence
SMS	Supermassive Star
MBH	Massive Black Hole
Pop.III	Population three/Third generation stars
MESA	Modules for Experiments in Stellar Astrophysics

2 NUMERICAL METHODS

We model the evolution of rapidly accreting SMSs in massive, hot halos in the MESA stellar evolution code from birth through to their collapse. The data is collated from the average of multiple profiles MESA outputs which we then analyse and compare current data.

MESA was chosen as a stellar evolution code for this project due to MESAs capabilities in simulating stars with zero metallicity and rapid mass gain.. Additionally, MESA is effective in accurately modelling a stars entire evolution right from formation through to its collapse. A more detailed description of the capabilities of this software can be found in Paxton et al. (2010); Paxton et al. (2011, 2013).

Also, MESA already has many in-built tools for analysis including Hertzbrung-Russel Diagrams, Kippenhahn Diagrams, and Taylor Diagrams. This makes it useful to use for stellar astrophysics modelling as almost everything required to do effective research is in-house.

MESA treats convection as a diffusive process across the stars life-cycle, using the assumption there is a reduction in the diffusion coefficient with an exponential factor for mixing length at the boundaries between convective and radiative layers as a function of stellar radius;

$$D = D_0 e^{-\frac{2z}{f_{CMB}^{AP,O}}} \quad (1)$$

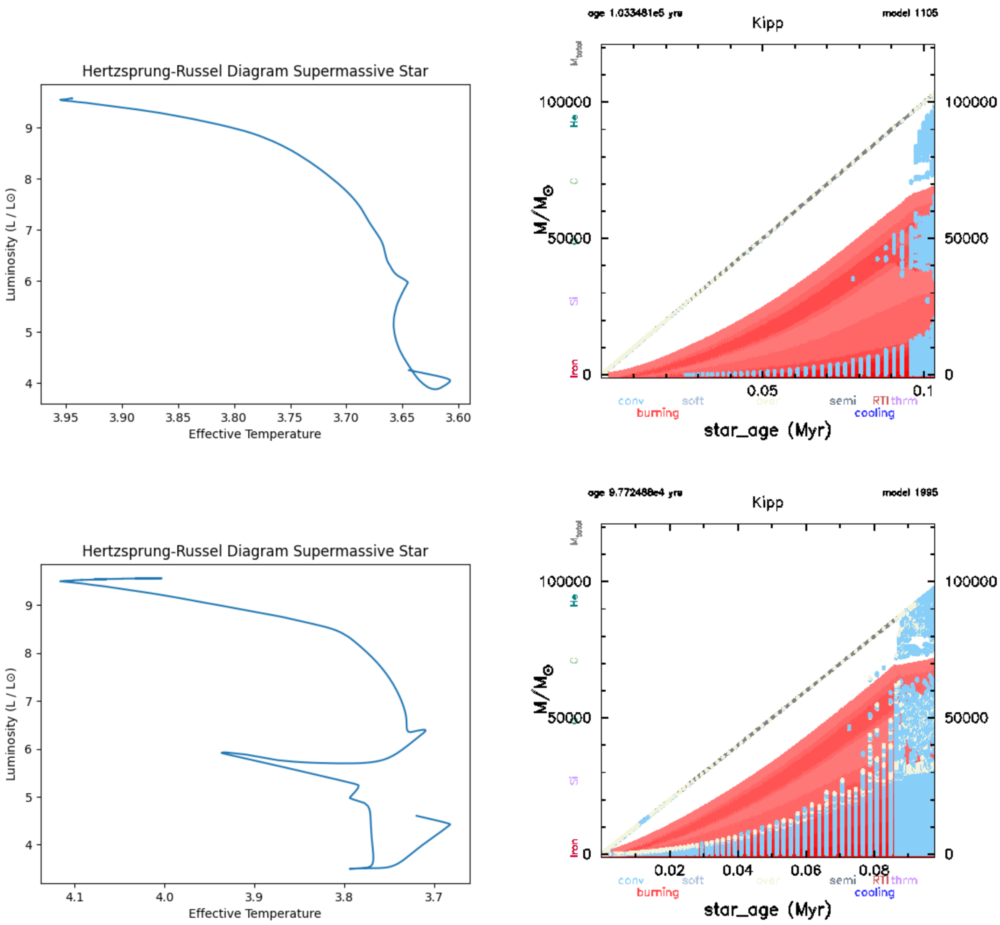

Figure 2. Left: Hertzsprung Russel diagrams of two SMSs MESA modelled showing its journey through its main sequence and a non-standard collapse with no signs of a standard supernova. Right: Kippenhahn diagrams of two SMSs MESA modelled showing an exponential mass growth and more burning regions (*red*) than mixing regions (*blue*).

where D_0 is the diffusion coefficient at a distance of $f_{CMB}H_{P,S}$ inside the convective zone from the Schwarzschild boundary, and D is the diffusion coefficient as a function of distance z from the boundary location and f_{CMB} is a free parameter. More details can be found in Paxton et al. (2010) and Jones et al. (2015).

2.1 15 $M_\odot$ Test Case

To investigate the accuracy of the results our MESA models output and our analysis scripts, it is necessary to run them on a test case. In this case, we first ran a 15$M_\odot$, non-accreting star. Modifications had to be made to the original stellar code to allow the star to evolve through its main sequence to post-main sequence.

The models output accurate results as seen in Figure 1 and can be verified in Doom (1982); Palma (2018).

Figure 1 shows the MESA model that aligns with what you might expect from a star more massive then the sun. That is, a journey up the Zero Age Main Sequence (ZAMS) with predominantly Hydrogen core burning which is then overtaken by Helium core burning with a Helium flash.

Then the star begins the Red-Giant post-main sequence phase where the star begins to cool and retain luminosity, which implies the star would be expanding over time.

It is also apparent that the majority of high energy burning occurs at the stars birth and decreases over time, with a growing radiative region and towards the end of its life there is maximum efficiency in heat transfer. This is typical of massive stars (Weaver & Woosley 1980).

MESA does not model a star collapsing into a Type II supernovae for the simple reason that if it did you it would not necessarily retain the useful aspects of each diagram as the effective temperatures and luminosity would increase dramatically, and over a very short amount of time compared to the rest of the stars lifetime.

2.2 Primordial Supermassive Star

While the test case of a 15$M_\odot$ star is indicative of what we may expect to see from a primordial SMS, other parameters must be taken into account.

We simulated this star in an atomically cooling halo, allowing for a constant accretion rate of 1 $M_\odot yr^{-1}$ by using controls available in MESA by simulating a mass change of this amount and making the accreted material the same as the material on the surface of the modelled star.

Additionally, we used corrections for the kind of extreme physics the star core would be experiencing. The energy and stellar structure equations provided by MESA was kept for this model, however the corrections for the general relativistic instability were also included.

We used an exponential, non-burning function for the overshooting to take into account the effects as described in Wagle et al. (2019). This is because of the general relativistic instability as aforementioned, as the small contributory effect of thermal photons would be a compounded as 0.1% in each iteration of the model. Additionally, the rapid growth of the star would be due to cosmological flows within the stars environment and can be seen in Figure 2.

Overshooting of the convective core of these stars due to their high mass (Claret & Torres 2017) play an important role in their evolution. Along with the rapid growth in mass and non-burning convective overshooting that Yoon et al. (2012) illustrates are characteristics of Pop.III Supernova progenitor stars.

For more details section *7.3.3* of Paxton et al. (2010) where they model a star of zero metallicity and zero mass loss is comparable to this model, despite their model reaching $1000\mathrm{M}_{\odot}$.

One of the goals of this model is to test the general relativistic controls in MESA and compare it to that of the G_{rel} corrections in KEPLER, both of which simulate the star in a very massive gaseous cloud (Chandrasekhar 1964) analogous to that SMSs form in.

The general relativistic equations are not the same in KEPLER and MESA. In the KEPLER code the Newtonian gravitational constant G is replaced by

$$G_{rel} = G\left(1 + \frac{P}{\rho c^2} + \frac{2GM_r}{rc^2} + \frac{4\pi P r^3}{M_r c^2}\right) \tag{2}$$

where ρ is the mass density, M_r is the mass enclosed within a radius r, P is the pressure, and c is the speed of light, an approximation that can be found in Fuller et al. (1986); Haemmerlé et al. (2018b)

This linearisation is not the case however in MESA, the relativistic control within MESA proposes a similar term to the spherically symmetric Schwartzschild term from a Black Hole geodesic metric where;

$$G = G_0\sqrt{1 - \frac{2G_0 M}{rc^2}} \tag{3}$$

where M and r is the mass and radius of the star respectively, c is the speed of light, and G_0 is Newton's gravitational constant.

3 RESULTS

Our models (Figure 2) showed that the early life of a primordial SMS is very similar to that of a smaller, present day star. However, the post-main sequence ending in a highly energetic thermonuclear supernovae that is evident in smaller stars is not in SMSs. Instead, we see that the SMS only travels through from ZAMS, up to the end of its Hydrogen burning where it then ceases and dies.

The effective temperature for this model star never exceeds 10^4K, and reaches luminosities of $10^{10}\ \mathrm{L}_{\odot}$. Also, the star spends the vast majority of its life cycle close to the Hayashi limit. These factors are typical of what Haemmerlé et al. (2018a) found.

With SMS luminosities reaching $\sim 3.6537 \times 10^{34}\,\frac{ergs}{second}$ and effective temperatures of $\sim 8,900$K[2]; this would place MESA's SMSs as supermassive "A" class stars (De Jager & Nieuwenhuijzen 1987).

There is quite a discernable difference between the two Hertsprung Russel diagrams of Figure 2. One being that the bottom diagram there is theoretically a "Helium flash", wherein the core of the SMS goes through a rapid transition of predominantly burning Hydrogen, to predominantly Helium. The other being that the bottom diagram exceeds the Hayashi limit, and exceeds temperatures of 16,000K. This would imply that the star is no longer in hydrostatic equillibrium and be in-falling, this could be the beginning of a direct collapse star death.

MESA output noticable different results between the $15\mathrm{M}_{\odot}$ and SMS models where the regions for convection, mixing, and radiation are different. This would be due to small differences in calculating each model. This was decided to be negligible due to the fact that the regions while in slightly different areas of the star and at different times in its life-cycle, the regions were of similar sizes in each model and still representative if the processes occurring in the stars.

We also see there are vaster zones of radiation and burning than can be observed in less massive stars. This is due to the extreme power output in primordial SMS cores compared to that of smaller, present day star cores (Stahler 1986).

4 CONCLUSION AND DISCUSSION

Our model shows that SMSs appears to grow to enormous masses, luminosities, and core temperatures and accrete masses of large magnitudes and grow rapidly. At the end of an SMS life cycle, it is supposed that instead of exploding in a highly energetic thermonuclear supernovae explosion, they form direct collapse black holes. The concept that these stars will end in a supernovae cannot be discarded, it is just not known if they will and many believe that with such high accretion layers supernovae may not be possible. This can also be explained with a general relativistic instability (Chen et al. 2014), wherein thermal photons would be so densely produced in the stars core that they would begin to contribute to the net gravity of the star. This would be a comparatively small amount, of the order 0.1% of the total gravity, however this would be enough to promote star contraction and expansion. Eventually the star would contract to a point where it does not have the necessary energy to increase back to an equilibrium position.

This would cause the core to collapse and accrete the outer layers of the star and the surrounding halo which encourages rapid growth and allows the black hole to reach the super-Eddington limit sooner and form a proto-galactic quasar (Small & Blandford 1992).

These results are in line with the findings of Hosokawa et al. (2013) wherein these stars would remain in the 8,000-10,000K due to H^- opacities in the stellar atmosphere. However, further analysis would have to be conducted to verify this as blue SMSs cannot be approximated as black bodies due to their much higher ionising fluxes because of high surface temperatures of 20,000-30,000K, and the majority of this is absorbed by the stars own atmospheres.

[2] for the purposes of star classification, we ignore the extreme temperature peak of the second model, this is due to the assumption that can be found in section **3, par.2**

As we have measured the effective temperatures of these SMSs, we assume the surface temperature would be similar to that of a black body with the same mass and luminosity. In which case this would support the findings of Haemmerlé et al. (2018a) and Surace et al. (2019), and offer an alternative conclusion to the studies that theorises primordial SMSs are cool, red hypergiants (Kohler 2019).

Further research would be valuable in this field as this article serves only as a general overview for this model. More specifically, investigating a variable accretion rate and binary star collapses.

In the Woods et al. (2017) article the authors find SMSs reach the relativistic instability effects when they reach masses of $150,000$ - $330,000$ $M_\odot$, however in our simulations we find that the effects due to the relativistic instability potentially begins past 10^4 $M_\odot$ leading to numerical difficulties at $10^5 M_\odot$ resulting in the code terminating. Further investigation is required to verify this, a method of this would be to measure the γ_1 profile against the mass of the star and observe the stability criteria and if it is violated, then this would indicate early core collapse.

The final mass of the SMS may not necessarily reach the mass at collapse for two potential reasons:

- Numerical instability may be causing the code to terminate.
- The relativistic instability is pulsational (Chandrasekhar 1964), relevant controls have not been included in this model.

Consequentially, more consistent hydrodynamics is required to fully capture the general relativistic instability.

References

Agarwal B., Smith B., Glover S., Natarajan P., Khochfar S., 2016, Monthly Notices of the Royal Astronomical Society, 459, 4209
Bañados E., et al., 2018, Nature, 553, 473
Chandrasekhar S., 1964, ApJ, 140, 417
Chen K.-J., Heger A., Woosley S., Almgren A., Whalen D. J., Johnson J. L., 2014, The Astrophysical Journal, 790, 162
Claret A., Torres G., 2017, The Astrophysical Journal, 849, 18
De Jager C., Nieuwenhuijzen H., 1987, Astronomy and Astrophysics, 177, 217
Doom C., 1982, Astronomy and Astrophysics, 116, 308
Fan X., et al., 2006, The Astronomical Journal, 131, 1203
Freese K., Bodenheimer P., Spolyar D., Gondolo P., 2008, The Astrophysical Journal Letters, 685, L101
Fuller G. M., Woosley S. E., Weaver T. A., 1986, ApJ, 307, 675
Haemmerlé L., Woods T. E., Klessen R. S., Heger A., Whalen D. J., 2018a, Monthly Notices of the Royal Astronomical Society, 474, 2757
Haemmerlé L., Woods T. E., Klessen R. S., Heger A., Whalen D. J., 2018b, ApJ, 853, L3
Hirano S., Hosokawa T., Yoshida N., Kuiper R., 2017, Science, 357, 1375
Hosokawa T., Yorke H. W., Inayoshi K., Omukai K., Yoshida N., 2013, ApJ, 778, 178
Jones S., Hirschi R., Pignatari M., Heger A., Georgy C., Nishimura N., Fryer C., Herwig F., 2015, Monthly Notices of the Royal Astronomical Society, 447, 3115
Kohler S., 2019, AAS Nova Highlights
Latif M., Volonteri M., 2015, Monthly Notices of the Royal Astronomical Society, 452, 1026
Latif M., Niemeyer J., Schleicher D., 2014a, Monthly Notices of the Royal Astronomical Society, 440, 2969
Latif M., Bovino S., Van Borm C., Grassi T., Schleicher D., Spaans M., 2014b, Monthly Notices of the Royal Astronomical Society, 443, 1979
Lodato G., Natarajan P., 2006, Monthly Notices of the Royal Astronomical Society, 371, 1813
Mortlock D., et al., 2009, Astronomy & Astrophysics, 505, 97
Mortlock D. J., et al., 2011, Nature, 474, 616
Palma D. C., 2018, The Evolution of Massive Stars and Type II Supernovae, `https://www.e-education.psu.edu/astro801/content/l6_p5.html`
Paxton B., Bildsten L., Dotter A., Herwig F., Lesaffre P., Timmes F., 2010, The Astrophysical Journal Supplement Series, 192, 3
Paxton B., Bildsten L., Dotter A., Herwig F., Lesaffre P., Timmes F., 2011, ApJS, 192, 3
Paxton B., et al., 2013, ApJS, 208, 4
Peimbert M., 2008, The Primordial Helium Abundance (`arXiv:0811.2980`)
Schauer A. T., Regan J., Glover S. C., Klessen R. S., 2017, Monthly Notices of the Royal Astronomical Society, 471, 4878
Small T. A., Blandford R. D., 1992, Monthly Notices of the Royal Astronomical Society, 259, 725
Spolyar D., Freese K., Gondolo P., 2008, Phys. Rev. Lett., 100, 051101
Stahler S. W., 1986, Publications of the Astronomical Society of the Pacific, 98, 1081
Surace M., Zackrisson E., Whalen D. J., Hartwig T., Glover S., Woods T. E., Heger A., Glover S., 2019, Monthly Notices of the Royal Astronomical Society, 488, 3995
Volonteri M., Silk J., Dubus G., 2015, The Astrophysical Journal, 804, 148
Wagle G. A., Ray A., Dev A., Raghu A., 2019, The Astrophysical Journal, 886, 27
Weaver T. A., Woosley S., 1980, Ann. New York Acad. Sci, 336, 335
Whalen D., Abel T., Norman M. L., 2004, The Astrophysical Journal, 610, 14
Whalen D. J., Fryer C. L., Holz D. E., Heger A., Woosley S. E., Stiavelli M., Even W., Frey L. H., 2012, The Astrophysical Journal Letters, 762, L6
Willott C. J., et al., 2009, The Astronomical Journal, 137, 3541–3547
Wise J. H., Regan J. A., O'Shea B. W., Norman M. L., Downes T. P., Xu H., 2019, Nature, 566, 85
Woods T., Heger A., Whalen D. J., Haemmerlé L., Klessen R. S., 2017, The Astrophysical Journal Letters, 842, L6
Yoon S.-C., Dierks A., Langer N., 2012, Astronomy & Astrophysics, 542, A113

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