Evolution and Nucleosynthesis of Very Massive Primordial Stars

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We investigate the evolution, final fate, and nucleosynthetic yields of rotating and non-rotating very massive stars (VMS) of zero metallicity. First we address the issue of mass loss during hydrogen burning due to vibrational instabilities. We find that these objects are much more stable than what was found in previous studies of VMS of solar composition, and expect only negligible mass loss driven by the pulsations. As these stars thus reach the end of their evolution with massive helium cores, they encounter the pair-creation instability. We find that for helium core masses of $\sim 64 \ldots 133 M_\odot$ these stars are completely disrupted with explosion energies of up to $\sim 10^{53}$ erg and eject up to $\sim 60 M_\odot$ of $^{56}$Ni. Stars with more massive helium cores collapse into black holes. We present the first calculations that follow the collapse of such a massive rotating star and predict that X-ray burst and significant gravitational wave emission could result.

1. INTRODUCTION

Recently, three-dimensional cosmological simulations have reached sufficient resolution on small scales to begin to address the star formation problem of the first generation of so-called Population III (Pop III) stars \cite{1,2}. Though the formation and nature of the first generation of metal-free stars have been investigated since over thirty years \cite{3–7, and many others}, the extent to which they differed from present day stars in ways other than composition is still debated. While considerable uncertainty remains, these simulations suggest that the first generation of stars may have been quite massive, $\sim 100 - 1000 M_\odot$ \cite{8–10}, giving us motivation to examine the properties, evolution, and fate of such stars.

2. VIBRATIONAL (IN-)STABILITY AND MASS LOSS

Above a critical mass, main sequence stars are vibrationally unstable due to the destabilizing effect of nuclear reactions in their central regions ($\epsilon$-mechanism) \cite{11,12}. According to non-linear calculations, such an instability leads to mass loss rather than catastrophic disruption \cite{13,13}. Previous investigations of stars of solar-like compositions or slightly metal-poor stars \cite{12,16–20} indicated that stars above a few $100 M_\odot$ would lose a substantial amount of mass during hydrogen burning. However, the structure of metal-free stars
Figure 1. Post-explosive nucleosynthetic yields of helium cores as a function of mass (black lines; left axis). $^{20}$Ne and $^{36}$Ar have yields similar to those of respectively $^{24}$Mg and $^{40}$Ca. The thick gray line gives the explosion energy in “foe” (1 foe = $10^{51}$ erg, about the explosion energy of a “typical” core collapse supernova; right axis).

is significantly different from those that even contain a trace of initial metals. We have thus performed, to our knowledge, the first stability analysis of zero metallicity stars with $100 \, M_{\odot} \leq M \leq 500 \, M_{\odot}$.

We find that the different structure and the higher central temperatures of these stars make them less vibrationally unstable, i.e., the timescale for the growth of the amplitude is much longer, and thus, based on the non-linear calculations of [13], we derive considerably lower mass loss rates than for more metal rich counterparts, and find that even our $500 \, M_{\odot}$ star loses only a negligible amount of mass during central hydrogen burning. During central helium burning only stars with initial masses above $\sim 300 \, M_{\odot}$ become pulsationally unstable during the last few 10,000 yr of their evolution. Therefore we estimate that stars of $\lesssim 500 \, M_{\odot}$ can even retain their hydrogen envelope until they encounter the pair creation instability. A more detailed description of our analysis can be found in [21].

3. NUCLEOSYNTHETIC YIELDS OF PAIR CREATION supernovae

The evolution of very massive stars has already been followed by many authors before [22, e.g.]. We followed the evolution and nucleosynthesis of rotating and non-rotating VMS Pop III stars from onset of hydrogen burning through the electron-positron pair creation instability until one year after the explosion [23], using recent stellar “input physics” and
extended nuclear reaction networks.

In Fig. 1 we give the results of calculations of non-rotating plain helium cores evolved without mass loss. It displays the yields of the ejecta as a function of helium core mass and the resulting explosion energy. For a $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ rate of $1.7 \times$ that of $^{24}$, in the extreme case of a 133.3 $\text{M}_\odot$ helium core we find an explosion energy of about $9.4 \times 10^{52}$ erg and ejection of 57 $\text{M}_\odot$ of $^{56}\text{Ni}$, almost half of all ejecta. The ejecta from these objects are dominated by “$\alpha$-nuclei”, but some nickel isotopes are made in the $\alpha$-rich freeze-out in the center of the most massive cores. Essentially no elements above the iron group are produced. Below the iron group, the elements of even charge number are produced in about solar abundance ratios, while elements of odd mass number are strongly underproduced.

Below $\sim 64 \text{M}_\odot$ we do not find prompt explosions of the helium cores, but after a strong pair-instability induced pulse the outer layers are ejected while the central parts of the star fall back and contract again and are either disrupted in subsequent pulses or evolve through to iron core collapse $^{25}$ and could become a collapsar, similar to the models of $^{26}$. Above $\sim 133 \text{M}_\odot$ the photo-disintegration of heavy elements into $\alpha$-particles, and $\alpha$-particles into nucleons, consumes so much energy that the center of the star continues to collapse into a black hole (see below). Only in the mass range shown in Fig. 1, which corresponds to initial stellar mass of $\sim 150 \ldots 250 \text{M}_\odot$, the star is completely disrupted in one pulse.

4. SIMULATIONS OF THE COLLAPSE TO A BLACK HOLE

We have followed the collapse of a rotating 300 $\text{M}_\odot$ stars that had a rotation of 10% Keplerian on the zero-age main sequence and which formed a $\sim 180 \text{M}_\odot$ helium core. The 1D model was mapped into a 2D Lagrangian SPH code when the central density exceeded $5 \times 10^{10}$ g cm$^{-3}$ and the further evolution was followed including, for the first time, neutrino trapping during the collapse. Sufficient angular momentum was present for triaxial deformations to grow significantly in the “proto-black hole”, with the possible consequence of a strong gravity wave signal. After the formation of the initial black hole, it accreted mass to $\sim 140 \text{M}_\odot$ at a rate of $10 \ldots 100 \text{M}_\odot$ s$^{-1}$. At this point, a centrifugally supported disk forms that may produce jets along the poles through magneto-hydrodynamical effects $^{27}$. Though the efficiencies of the mechanisms under consideration are still very speculative, such a jet could lead either to an energetic, jet-driven explosion or an x-ray transient, depending on whether the hydrogen-rich envelope of the star is still present or has been lost to a possible binary companion star. A more detailed description is given in $^{28}$.

5. SUMMARY AND CONCLUSIONS

Recent results on the formation of Pop III stars indicate that very massive stars of zero metallicity could have formed. Our analysis of the pulsation properties indicates that stars of $\lesssim 500 \text{M}_\odot$ are far less vibrationally unstable than previously though and thus may reach the end of their evolution as objects with massive helium cores that encounter the pair-creation instability. This has interesting consequences for the nucleosynthetic yield from these objects, and may even allow for the observation of their explosions despite the high
red shift. Above an initial mass of \( \sim 300 \, M_\odot \) the core collapses into a black hole and may cause an X-ray burst or a strong gravity wave signal that may be accessible to experiments in the near future.

The survival of these objects as very massive stars until the end of their evolution also has interesting consequences for the re-ionization of the early universe, as these VMS have an effective surface temperature of \( \sim 10^5 \, K \) \([29,21]\), which means that they very efficiently turn nuclear energy into ionizing photons.

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REFERENCES

1. J.P. Ostriker and N.Y. Gnedin, ApJ (1996) 472, L63.
2. T. Abel, P. Anninos, M.L. Norman, and Y. Zhang, ApJ (1998) 508, 518.
3. M. Schwarzschild and L. Spitzer, Observatory (1953) 73, 77.
4. T. Yoneyama, PASJ (1972) 24, 87.
5. T.W. Hartquist and A.G.W. Cameron, Ap&SS (1977) 48, 145.
6. F. Palla, E.E. Salpeter, and S.W. Stahler ApJ (1983) 271, 632.
7. J. Silk MNRAS (1983) 205, 705.
8. R.B. Larson, ESA Special Publications Series (SP-445), eds. F. Favata, A.A. Kaas, and A. Wilson (1999) in press, astro-ph/9912539.
9. T. Abel, G.L. Bryan, and M.L. Norman, ApJ (2000) in press, astro-ph/0002138.
10. V. Bromm, P.S. Coppi, and R.B. Larson, ApJ (1999) 527, L5.
11. P. Ledoux, ApJ (1941) 94, 537.
12. M. Schwarzschild and R. Härm, ApJ (1959) 129, 637.
13. I. Appenzeller, A&A (1970) 5, 355.
14. R.J. Talbot, ApJ (1971) 165, 121.
15. J.C.B. Papaloizou, MNRAS (1973) 162, 169.
16. R. Stothers and N.R. Simon, ApJ (1968) 152, 233.
17. M.L. Aizenman, C.J. Hansen, and R.R. Ross, ApJ (1975) 201, 387.
18. R. Stothers, ApJ (1992) 392, 706.
19. W. Glatzel and M. Kiriakidis, MNRAS (1993) 262, 85.
20. M. Kiriakidis, K.J. Fricke, and W. Glatzel, MNRAS (1993) 264, 50.
21. I. Baraffe, A. Heger, and S.E. Woosley, ApJ (2000) submitted, astro-ph/0009410.
22. J.R. Bond, W.D. Arnett, and B.J. Carr, ApJ (1984) 280, 825.
23. A. Heger and S.E. Woosley, ApJ (2000) in preparation.
24. G.R. Caughlan, W.A. Fowler, Atom. Data and Nucl. Data Tables (1988) 40, 283.
25. S.E. Woosley, in Nucleosynthesis and Chemical Evolution, Saas-Fee Advanced Course (1986) 15, 1.
26. A.I. MacFadyen, S.E. Woosley, and A. Heger, ApJ (2000) accepted.
27. R.D. Blanford and R.L. Znajek, MNRAS (1977) 179, 433.
28. C.L. Fryer, S.E. Woosley, and A. Heger, ApJ (2000) accepted.
29. D. Ezer and A.G.W. Cameron, Ap&SS (1971) 14, 399.