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THE FIRST STARS

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Abstract. Pop III stars are the key to the character of primeval galaxies, the first heavy elements, the onset of cosmological reionization, and the seeds of supermassive black holes. Unfortunately, in spite of their increasing sophistication, numerical models of Pop III star formation cannot yet predict the masses of the first stars. Because they also lie at the edge of the observable universe, individual Pop III stars will remain beyond the reach of observatories for decades to come, and so their properties are unknown. However, it will soon be possible to constrain their masses by direct detection of their supernovae, and by reconciling their nucleosynthetic yields to the chemical abundances measured in ancient metal-poor stars in the Galactic halo, some of which may bear the ashes of the first stars. Here, I review the state of the art in numerical simulations of primordial stars and attempts to directly and indirectly constrain their properties.

Keywords: early universe, galaxies: high redshift, stars: early type, supernovae: general, radiative transfer, hydrodynamics, shocks.

1. The Simulation Frontier

Unlike with star formation in the Galaxy today, there is little disagreement over the initial conditions of star formation in the primordial universe. The original numerical simulations suggested that Pop III stars formed in small pregalactic structures known as cosmological minihalos at $z \sim 20 \div 30$, or ~ 200 Myr after the Big Bang [1–4, 24]. These models predicted that the stars formed in isolation, one per halo, and that they were $100 \div 500\,M_\odot$. Pop III stars profoundly transformed the halos that gave birth to them, expelling their baryons in supersonic ionized flows and later exploding as supernovae (e.g. [21, 38, 39, 44]). Radiation fronts from these stars also engulfed nearby halos, either promoting or suppressing star formation in them, thereby regulating the rise of the first stellar populations [11, 15, 30, 33, 34, 40, 41].

The original estimates of Pop III stellar masses were not obtained by modeling the actual formation and evolution of the stars. They were derived by comparing infall rates at the center of the halo at early stages of collapse to Kelvin–Helmholz contraction times to place upper limits on the final mass of the star. Later simulation campaigns in the same vein revealed a much broader range of final masses for Pop III stars, $30 \div 300\,M_\odot$ [27], and that they could form as binaries in a fraction of the halos [35]. Heroic numerical efforts have only recently achieved the formation of a hydrostatic protostar at the center of the halo [51] and the collapse of the central flow into an accretion disk [6, 9, 10, 31, 32].

In particular, the disk calculations indicate that they are unstable to fragmentation, raising the possibility that Pop III stars may have only been tens of solar masses, not hundreds, and that they may have formed in small swarms of up to a dozen at the centers of primeval halos. Computer models of ionizing UV breakout in the final stages of Pop III protostellar disks have also found that the I-front of the nascent star exits the disk in bipolar outflows that terminate accretion onto the star and mostly evaporate the disk by the time the star reaches $\sim 40\,M_\odot$ [13]. This result reinforces the sentiments of some in the community that while the Pop III IMF was top-heavy, primordial stars may only have been $10 \div 40\,_\odot$.

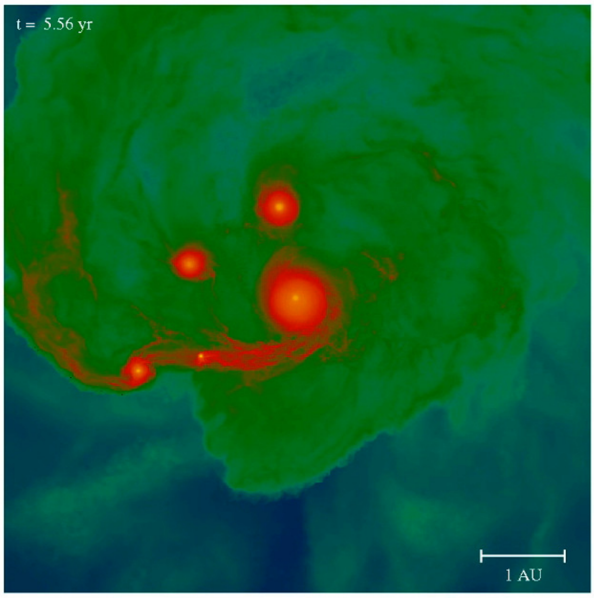

Figure 1. The formation and fragmentation of a Pop III protostellar disk in the Arepo code [10].

1.1. High-mass or low-mass Pop III stars?

In spite of their increasing sophistication, these simulations should be taken to be very preliminary for several reasons. First, Pop III accretion disks form in smoothed-particle hydrodynamics (SPH) models but not in adaptive mesh refinement (AMR) simulations, although the AMR models have not evolved the collapse of the halo to the times achieved by SPH calculations. This raises the question of whether one technique better captures the transport of angular momentum out of the center of the cloud than the other, and whether accretion is ultimately spherical or through a disk. Second, the stability of the disk itself remains an open question because although the simulations can now fully resolve the disk they do not yet incorporate all of its relevant physics. In particular, they lack high-order radiation transport, which regulates the thermal state of the disk and its tendency to fragment. Furthermore, the role of primordial magnetic fields in the formation and evolution of the disk is not well understood [36, 48].

The use of sink particles to represent disk fragments in the original SPH simulations of Pop III protostellar disk formation called into question the longevity of the fragments. Once they are created in the simulations they are never destroyed, unlike real fragments that could be torn apart by gravitational torques and viscous forces [25]. More recent moving mesh simulations performed with the Arepo code that do not rely on sink particles find that the fragments persist but only evolve the disk for $10 \div 20$ yr [10]. Perhaps most importantly, no simulation has followed the disks for more than a few centuries, far short of the time required to assemble a massive star. Thus, it remains unclear if the fragments in the disk remain distinct objects or merge with the largest one at the center, building it up into a very massive star over time through protracted, clumpy accretion.

1.2. Accretion cutoff and the final masses of Pop III stars

This latter point directly impacts estimates of final masses for Pop III stars inferred from numerical simulations that attempt to model ho ionizing UV from the star reverses infall and evaporates the accretion disk. At the heart of such models is a simple recipe for the evolution of the protostar that provides a prescription for its radius and luminosity as a function of time and acquired mass. The Hosokawa et al. [13] 2D calculations take the growth of the protostar to be relatively steady, in which case it contracts and settles onto the main sequence at $\sim 30\,M_\odot$. At this point the star becomes extremely luminous in ionizing UV radiation that halts accretion onto the star in a few hundred kyr at a final mass of $\sim 40\,M_\odot$. If accretion instead turns out to be clumpy, the protostar could remain puffy and cool and reach much larger masses before burning off the disk.

A finer point is that all current accretion cutoff simulations evolve both radiation and hydrodynamics on the Courant time, a practice which is known to lead to serious inaccuracies in I-front propagation in density gradients [43]. Such coarse time steps may result in premature I-front breakout and accretion cutoff, and hence underestimates of the final mass of the star. Three dimensional simulations with more accurate radiation–matter coupling schemes, both steady and clumpy accretion scenarios, more realistic prescriptions for protostellar evolution based on nucleosynthesis codes such as KEPLER [37, 49] and a variety of halo environments may better constrain the Pop III IMF. However, in judging the power of such simulations to model the masses of the first stars, it should be remembered that no simulations realistically bridge the gap in time between the formation and fragmentation of a protostellar disk and its photoevaporation up to a Myr later. We note in passing that fragments can also stop accreting if they are ejected from the disk by 3-body gravitational effects [9, 17]. These fragments could become very low-mass Pop III stars ($\sim 1\,M_\odot$); if so, some of them may live today.

2. Constraining the Pop III IMF with stellar archaeology

Unfortunately, because they lie at the edge of the observable universe, individual Pop III stars will remain beyond the reach of direct detection for decades to come, even with their enormous luminosities [29] and the advent of the next generation of near infrared (NIR) observatories such as the James Webb Space Telescope (JWST) and the Thirty-Meter Telescope (TMT). However, there have been attempts to indirectly constrain the masses of Pop III stars by comparing the cumulative elemental yield of their supernovae to the fossil chemical abundances found in ancient metal-poor stars in the Galactic halo, some of which may be second-generation stars. Stellar evolution models indicate that $15 \div 40\,M_\odot$ primordial stars died in core collapse (CC) supernovae (SNe) and that $40 \div 140\,M_\odot$ stars collapsed to black holes, perhaps with violent pulsational mass loss prior to death [12]. Pop III stars between 140 and $260\,M_\odot$ can die in pair-instability (PI) SNe, with energies up to 100 times those of Type Ia SNe that completely unbind the star and leave no compact remnant (Chatzopoulos & Wheeler 2012 have recently discovered that rotating Pop III stars down to $65\,M_\odot$ can also die as PI SNe). These explosions were the first great nucleosynthetic engines of the universe, expelling up to half the mass of the progenitor in heavy elements into the early IGM. Primordial stars above $260\,M_\odot$ collapsed directly to black holes, with no mass loss.

Joggerst et al. [18] recently calculated the chemical imprint of low-mass Pop III SNe on later generations of stars by modeling mixing and fallback onto the central black hole in $15 \div 40\,M_\odot$ Pop III core collapse explosions with the CASTRO AMR code. As shown

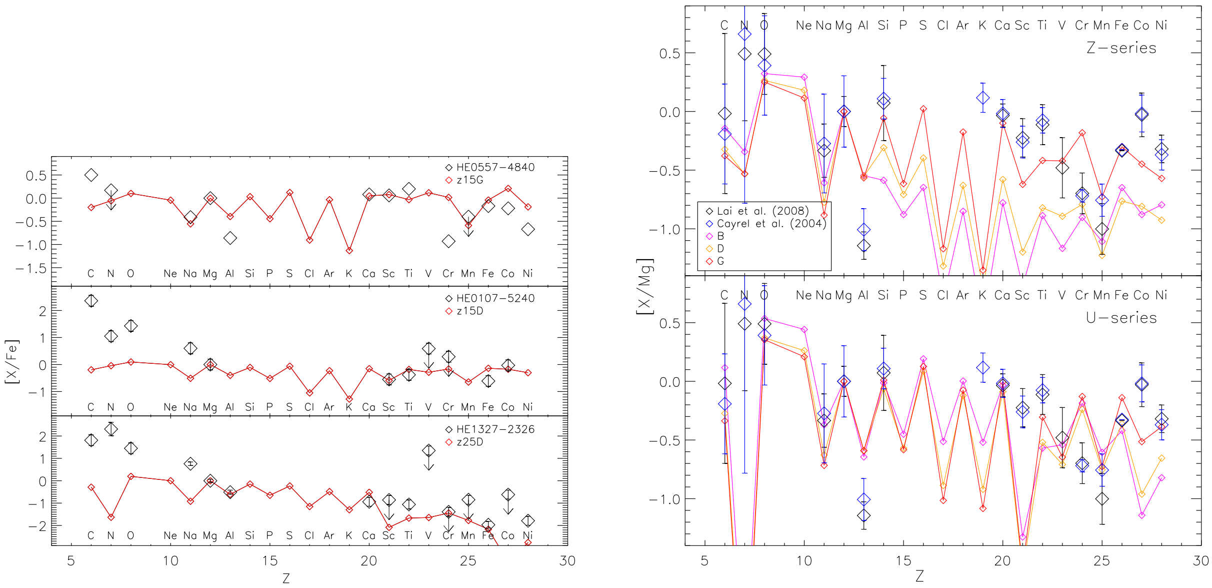

FIGURE 2. Comparing Pop III SN yields to the chemical abundances of three of the most metal-poor stars (left panel) and the extremely metal-poor (EMP) stars in the Cayrel et al. [5] and Lai et al. [22] surveys (right panel). In the left panel, the abundances in HE0557-4840 agree well with the yields from SN model z15G in the Joggerst et al. [18] study. In the right panel we show that higher explosion energy rotating $Z = 0$ stars reproduce EMP abundances well. The existence of $15\,M_\odot$ Pop III stars is required to produce this good agreement with observations.

in Fig. 2, a simple power-law IMF average of the elemental yields of these explosions is in good agreement with the fossil abundances in a sample of 130 extremely metal poor stars with $Z < 10^{-4}\ Z_\odot$ [5, 22]. Although these results suggest that low-mass Pop III stars shouldered the bulk of the chemical enrichment of the early IGM, $40 \div 60\,M_\odot$ hypernova explosions, whose energies are intermediate to those of CC and PI SNe, may also have contributed metals at high redshifts [16].

To date, the telltale odd-even nucleosynthetic signature of PI SNe has not been found in the fossil abundance record, leading some to assert that Pop III stars could not have been very massive. However, the odd-even effect may have been masked by observational bias in previous surveys [19]. Reconciling Pop III SN yields to the elemental patterns in metal-poor stars is still in its infancy for several reasons. First, only small numbers of extremely metal-poor stars have been discovered to date, and larger sample sizes would better constrain early SN yields. Second, measurements of some elements in low-metallicity stars are challenging and in the past have been subject to systematic error. Finally, there are many intervening hydrodynamical processes between the expulsion of the first metals and their uptake into new stars that are not yet understood.

3. Finding the first cosmic explosions

Detection of Pop III SNe would unambiguously probe the masses of primordial stars for the first time. Since these explosions are 100,000 times brighter than either their progenitors or the primitive galaxies that host them, they could be found by JWST or the Wide-Field Infrared Survey Telescope (WFIRST). However, unlike the Type Ia SNe used to constrain cosmic acceleration, light from primeval supernovae must traverse the vast cosmic web of neutral hydrogen that filled the universe prior to the epoch of reionization. Lyman absorption by this hydrogen removes or scatters most of the light from ancient supernovae out of our line of sight, obscuring them.

Whalen et al. [45–47] have calculated JWST NIR light curves for Pop III pair-instability SNe with the Los Alamos RAGE and SPECTRUM codes [7, 8], which are shown for $z = 10$, 15, 20 and 30 in Fig. 3. These simulations include radiation hydrodynamical calculations of the SN light curve and spectra in the local frame, cosmological redshifting, and Lyman absorption by intergalactic hydrogen. JWST detection limits at $2 \div 4\,\mu$m are AB magnitude $31 \div 32$, so it is clear that JWST will be able to detect the first cosmic explosions in the universe if they are PI SNe (and even perform spectrometry on them). Even given JWST's very narrow fields of view at high redshifts, recent calculations indicate that at least a few PI SNe should be present in any given JWST survey [14]. Also, because WFIRST detection limits will be AB magnitude 26.5 at $2.2\,\mu$m, it is clear from Fig. 3 that Pop III PI SNe will be visible to WFIRST out to $z \sim 15 \div 20$. Since it is an all-sky survey, and because this redshift range may favor the formation of very massive Pop III stars because of the rise of Lyman-Werner UV backgrounds [28], WFIRST will detect much larger numbers of Pop III SNe.

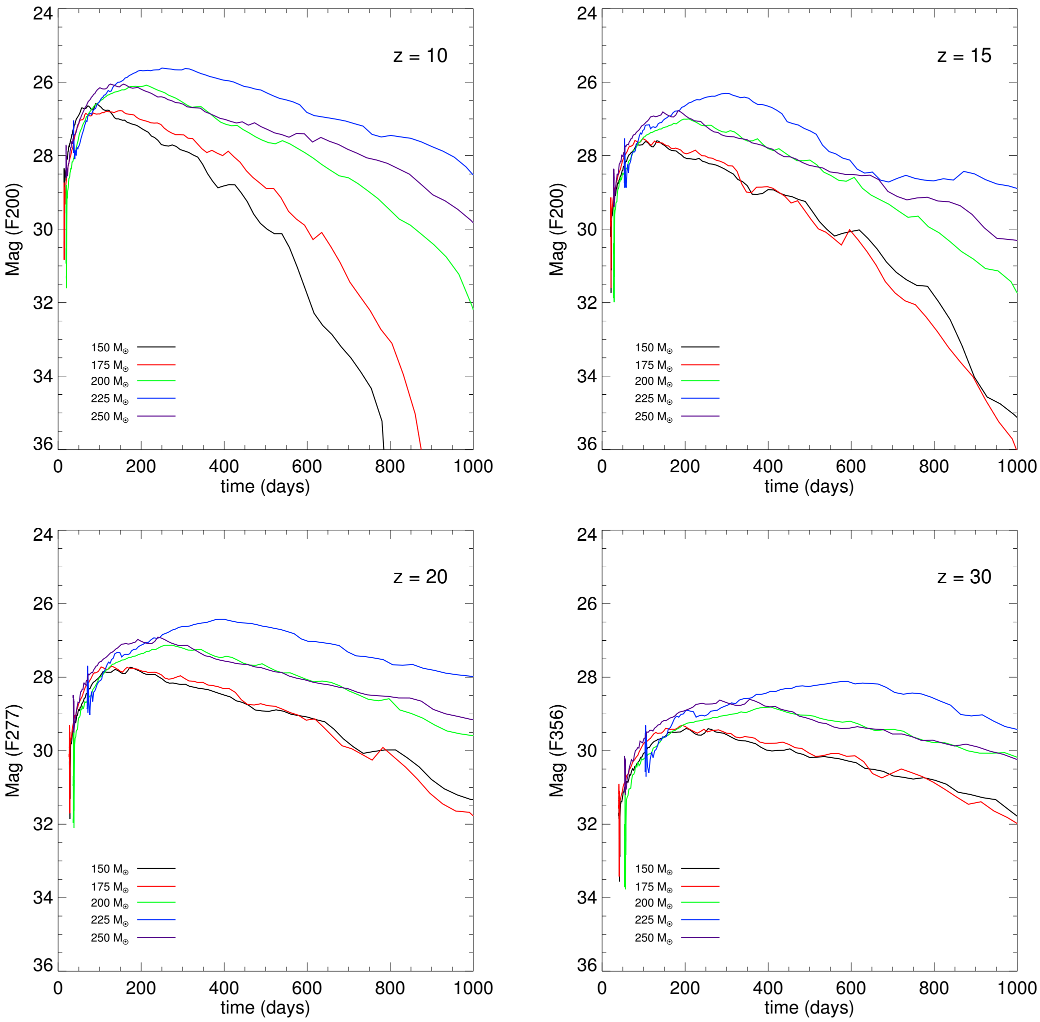

Figure 3. Pop III PI SN light curves for the JWST NIRCam. Clockwise from the upper left panel, the redshifts are $z = 10$, 15, 20 and 30. The optimum filter for each redshift is noted on the y-axis labels and the times on the x-axes are for the observer frame. F200, F277 and F356 are at 2.0, 2.77 and 3.56 µm, respectively.

Could Pop III SNe be detected at later stages by other means? Whalen et al. [40], found that most of the energy of Pop III CC SNe is eventually radiated away as H and He lines as the remnant sweeps up and shocks surrounding gas. At later epochs this energy would instead be lost to fine structure cooling by metals. In both cases the emission is too dim, redshifted and drawn out over time to be detected by any upcoming instruments. However, PI SNe deposit up to half of their energy into the cosmic microwave background (CMB) by inverse Compton scattering at $z \sim 20$ [21, 40] and could impose excess power on the CMB at small scales [26]. The resolution of current ground-based CMB telescopes such as the *Atacama Cosmology Telescope* and *South Pole Telescope* approaches that required to directly image Sunyaev-Zeldovich (SZ) fluctuations from individual Pop III PI SN remnants, so future observatories may detect them. Unlike PI SNe, CC SNe deposit little of their energy into the CMB at $z \sim 20$, and even less at lower redshifts because the density of CMB photons falls with cosmological expansion.

The extreme NIR luminosities of primordial PI SNe could contribute to a NIR background excess, as has been suggested for Pop III stars themselves, i.e. [20]. New calculations reveal that enough synchrotron emission from CC SN remnants is redshifted into the 21 cm band above $z \sim 10$ to be directly detected by the *Square Kilometer Array* (*SKA*) [23]. Somewhat more energetic hypernovae could be detected by existing facilities such as the *Extended Very-Large Array* (*eVLA*) and *eMERLIN*. PI SN remnants generally expand into ambient media that are too diffuse to generate a detectable synchrotron signal. Pop III SN event rates make it unlikely that they will be found in absorption at 21 cm at $z > 10$.

The detection of the first cosmic explosions will be one of the most spectacular discoveries in extragalactic astronomy in the coming decade, opening our first observational window on the era of first light and the end of the cosmic Dark Ages at $z \sim 30$. They will unveil the nature of primordial stars and constrain scenarios for early cosmological reionization, the process whereby the universe was gradually transformed from a cold, dark, featureless void into the vast, hot, ionized expanse of galaxies we observe today. At somewhat lower redshifts ($z \sim 10 \div 15$), detections of Pop III supernovae will probe the era of primitive galaxy formation, marking the positions of nascent galaxies on the sky that might otherwise have eluded detection by JWST. Finally, finding the first supernovae could also reveal the masses of the seeds of the supermassive black holes lurking at the centers of massive galaxies today.

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Discussion

Wolfgang Kundt — You spoke of a mass range ($> 40\,M_\odot$) for primordial stars for which they would collapse to black holes. Where are the nearest of them today?

Daniel Whalen — This is an excellent question. We recently published a letter (Whalen & Fryer 2012) in which we found that most $20 \div 40\,M_\odot$ Pop III black holes would be ejected from the cosmological halos that gave birth to them at velocities of $500 \div 1000\,\mathrm{km\,s^{-1}}$ by natal kicks due to asymmetries in the core-collapse engine. Such velocities are far above the escape velocity of any halo they would encounter for over a Hubble time, so there is a good chance that these black holes would be exiled to the voids between galaxies today. Black holes above $40\,M_\odot$ are unlikely to be born with kicks and remain in the halo, accreting and growing over cosmic time. These black holes are much more likely to reside in the galaxies into which their host halos were taken, a few of which could become the supermassive black holes found in the SDSS quasars today.

Maurice Van Putten — What fraction of the gas in a cosmological halo ends up in primordial stars?

Daniel Whalen — It is currently thought that the minimum halo mass for forming a Pop III star is $\sim 10^5\,M_\odot$ and that 1–10 stars are formed with masses of $30 \div 300\,M_\odot$. Thus, a conservative estimate is that $0.1 \div 1\,\%$ of the baryons in the halo are converted into stars, and that the rest are evicted from the halo by strong ionized flows over the life of the stars.