The First Stars: Formation of Binaries and Small Multiple Systems Athena Stacy¹, Thomas Greif², and Volker Bromm¹

¹University of Texas at Austin, USA, ²University of Heidelberg, Germany

Abstract

We investigate the formation of metal-free, Population III (Pop III), stars within a minihalo at z \sim 20 with a smoothed particle hydrodynamics (SPH) simulation, starting from cosmological initial conditions. Employing a hierarchical, zoom-in procedure, we achieve sufficient numerical resolution to follow the collapsing gas in the center of the minihalo up to number densities of 1012 cm⁻³. This allows us to study the protostellar accretion onto the initial hydrostatic core, which we represent as a growing sink particle, in improved physical detail. We continue our simulation for 5000 yr after the first sink particle has formed. During this time period, a disk-like configuration is assembled around the first protostar. The disk is gravitationally unstable, develops a pronounced spiral structure, and fragments into several other protostellar seeds. At the end of the simulation, a small multiple system has formed, dominated by a binary with masses ~ 40 M_{\odot} and ~ 10 M_{\odot}

Methodology These studies are performed using Gadget, a widely-tested three dimensional smoothed particle hydrodynamics (SPH) code. Simulations are carried out in a box size of 100 kpc (comoving) and initialized at z=99 with both DM particles and SPH gas particles. This is done in accordance with a LCDM cosmology with WL=0.7, WM=0.3, Wb=0.04, and h=0.7.

A preliminary run allows for location of the site of formation of the first minihalo. Three refinement levels are subsequently added such that in the final simulation a parent particle will be replaced by up to 512 child particles. This improves the mass resolution of the main simulation to < 1 M_{\odot} . Gas particles reaching densities above n=1012 cm-3 are replaced with sink particles. Gas particles which enter the radius of the sinks are removed from the simulation, and their mass is added to that of the sinks



Physical state of the collapsing core. The situation is shown just prior to the formation of the first sink particle. (a) Temperature; (b) free electron fraction; (c) molecular hydrogen fraction; and (d) adiabatic exponent γ_{ad} vs. density. The gas that collapses into the minihalo is heated adiabatically to ~ 1000K as it reaches n ~ 1 cm⁻³ (panel a). At this The gas that collapses into the minihalo is heated adiabatically to ~ 1000K as it reaches n ~ 1 cm⁻³ (panel a). At this point f_{tric} becomes high enough (panel c) to allow the gas to cool through H₂ rovibrational transitions to a minimum of ~ 200K, which is reached at n ~ 10⁴ cm⁻³ (panel a). Atter the onset of gravitational instability, the gas reaches yet higher densities, and is heated to a maximum of ~ 1000K once it approaches a density of ~ 10⁸ cm⁻³. At this density three-body reactions become important, and the gas is rapidly converted into fully molecular form (panel c). The increased H₂ cooling rate then roughly equals the adiabatic heating rate, and thus the highest density gas is nearly isothermal. As the gas is transformed into molecular form, the equation of state changes as well so that γ_{ad} evolves from 5/3 to approximately 7/5 (panel d). Gas that reaches 10¹² cm⁻³ is replaced with a sink particle. Im of T



Final simulation output shown in density projection along the x-z plane on progressively smaller scales, as labeled on each panel. White boxes denote the region to be depicted in the next-smallest scale. In the bottom four panels, the asterisk denotes the location of the first sink formed.

Top left: Entire simulation box. -- Top right: Minihalo and surrounding filamentary structure.

-Bottom right: Central 100 pc of minihalo. -Bottom left: Central 10 pc of minihalo.

Note how the morphology approaches an increasingly smooth, roughly spherical distribution on the smallest scales, where the gas is in quasihydrostatic equilibrium, just prior to the onset of runaway collapse.



Density projections of the central 5000 AU of simulation box at end of simulation (5000 yr after initial sink formation). The assembly of the disk-like configuration around the first sink particle, and the subsequent fragmentation into additional sinks, are visible here. On the left is shown the disk face-on, where it is evident that the growing disk is unstable and develops a pronounced spiral pattern, leading in turn to the formation of multiple high-density peaks. One the right is shown the disk edge-on, where the highly flattened structure is apparent.

sink	$t_{\rm form}~[\rm yr]$	$\rm M_{final}~[M_{\odot}]$	$r_{\rm init} \; [{\rm AU}]$	r_{final} [AU]
1	0	43	0	0
2	300	13	60	700
3	3700	1.3	930	1110
4	3750	0.8	740	890
5	4400	1.1	270	240



Around 300 vr after the first sink has formed, the disk becomes unstable to fragmentation and a second sink is created. By the end of our simulation we have 5 sink particles throughout the disk, described in the table. Compared to the two largest sinks (marked in the red box), the three smallest sinks are quite low-mass and have been present in the simulation for only a short time. The wo largest sinks seem to be the only long-term sinks in the simulation.



Left: Sink mass versus time since initial sink formation --Solid line: mass of the first sink particle over time in our calculation. --Red line: least-squares powerlaw fit to the sink mass over time (M \propto t^{0.55}). --Dash-dotted line: result obtained by Bromm & Loeb (2004). --Dotted line is the mass growth of the second largest sink.

since initial sink formation. --Solid line: accretion rate of the first sink particle throughout our --Red line: powerlaw fit to the mass

Right: Accretion rate versus time

accretion rate (dM/dt \propto t^{-0.45}). --Black dash-dotted line: accretion rate found by Bromm & Loeb (2004) --Red dotted line: their average accretion rate over the lifetime of a

Pop III star, 3 x 10⁶ yr. --Dotted line: accretion rate of the second largest sink.

-Green short-dash line and blue long-dash line: Shu accretion rates for isoth and 200 K mal gas at 700 K



Conce the initial sink particle has grown to ~10 M_g, the surrounding gas divides into a hot phase and cold phase. At this mass the gravitational force of the sink particle is strong enough to pull gas towards it with velocites sufficiently high to heat the gas to a maximum temperature of ~7.000K. The increasing mass of the sink causes a pressure wave to propagate outward from the sink and heat particles at progressively larger radii and lower density. The heated region extends out to ~ 2.000 AU at 5000 yr.



We do not include any radiative feedback effects here. However, McKee & Tan (2008) estimate that the accretion rate of a disk onto a Pop III star is not significantly reduced until the star has gained ~ 50 M_{\odot} , and we end our calculation somewhat before feedback effects have become too strong to ignore

We assess how important this neglected feedback would be up to the stage simulated here. In the left figure we compare the accretion luminosity L_{acc}, with the Eddington luminosity due to electron scattering (dashed line) and due to H⁻ opacity (dash-dot line). Solid red line is L_{acc} for the most massive sink. Dotted line is the precision of L_{acc} by Tan & Mckee (2004). Since L_{acc} stays below L_{Edd} , radiation pressure is not likely to significantly change the early accretion rates we have found.

1000 2000 3000 4000 5000 time [yr] Future work will consist of simulations that include radiative feedback in order to yield a better understanding of how and when disk accretion onto a primordial protostar may be terminated.