The First Stars: Formation of Binaries and Small Multiple Systems
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Abstract
We investigate the formation of metal-free, Population III (Pop III), stars within a minihalo at z ~ 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 $10^{12}$ 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 $W_\Lambda=0.7$, $W_{\text{M}}=0.3$, $W_{\text{b}}=0.04$, 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 < $1 M_\odot$.

One on the right is shown the disk edge-on, where the highly flattened structure is apparent.

Around 3000 yr 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 smallest 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 two largest sinks seem to be the only long-term sinks in the simulation.

> **Table 1.** Formation times, final masses, and distances from the main sink. We include all states still present at the end of the simulation.

### Disk mass:
- ~ 2nd largest sink
- ~ smaller sinks

### Disk radius:
- ~ $2000$ AU

#### Density projections of the central 5000 AU of simulation box at end of simulation (5000 yr after initial sink formation).

#### Disk mass:
- ~ $40 M_\odot$

#### Disk radius:
- ~ $2000$ AU

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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 $\gamma$ vs. density. The gas that collapses into the minihalo is heated adiabatically to ~ $10^4$ K as it reaches a density of ~ $10^4$ cm$^{-3}$. At this point $\gamma$ becomes high enough (panel c) to allow the gas to cool through $H_2$ vibrational transitions to a minimum of $T \sim 7000$ K. The increasing mass of the sink causes a pronounced cooling rate (dashed line) and due to $H_2$ opacity (dash-dot line). Solid red line is $L_{\text{acc}}$ (from McKee & Tan (2008)) estimate that the accretion rate of a disk onto a Pop III star, $3 \times 10^3$ yr.

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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 particle.

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**Right: Accretion rate versus time since initial sink formation.**

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**Left: Sink mass versus time since initial sink formation.**

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**Bottom right: Central 100 pc of minihalo.**

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**Bottom left: Central 100 pc of minihalo.**

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### Disk mass:
- ~ 2nd largest sink
- ~ smaller sinks