The First Stellar Clusters

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Overview

We present the results of simulations of the high-density, dust-cooling dominated regime that employ the equations of state of Omukai et al (2005). Our simulations include the effects of rotation, turbulence, and follow a large dynamical range of the collapse (ten orders of magnitude in density). A key feature is the use of sink particles to capture the formation and evolution of multiple collapsing cores, which enables us to follow the evolution of the star-forming gas over several free-fall timescales. We are therefore able to model the build-up of a stellar cluster. This contrasts with previous studies, which either follow the collapse of a single core to high densities (e.g. Abel, Bryan & Norman, 2002; Yoshida et al, 2006), or use sink particles to capture low density ($n < 10^6$ g cm^{-3}) fragmentation (e.g. Bromm et al, 2001).

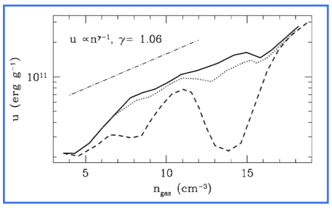
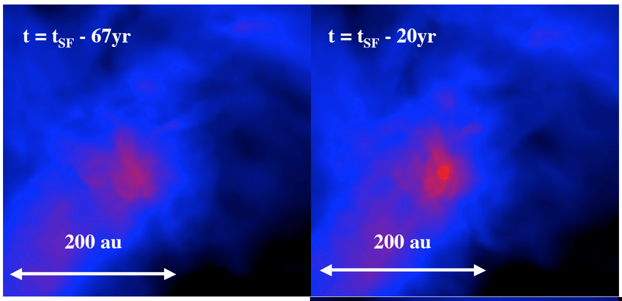
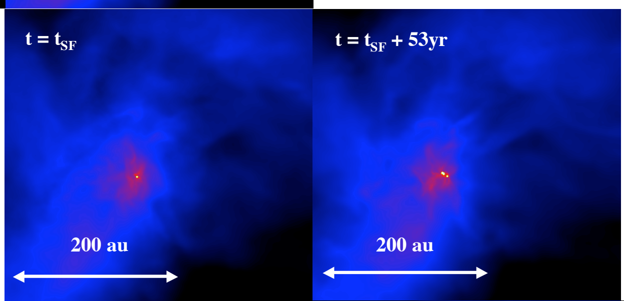


Figure 1: The three equations of state (EOSs) from Omukai et al (2005) that are used in our study. The primordial case (solid line), the $Z = 10^{-6}\ Z_{SUN}$ (dotted line), and $Z = 10^{-5}\ Z_{SUN}$ (dashed line), are shown alongside an example of a polytropic EOS with an effective gamma of 1.06.

Calculation Details

We use smoothed particle hydrodynamics to model the gas in our study, and employ sink particles (Bate, Bonnell & Price 1995) to capture to the formation of the protostars. Three equations of state (EOSs) from Omukai et al (2005) are used in this study, which include the effects of dust-cooling at low metallicities. They are shown above in Figure 1. Our clouds have 500 M_{SUN} and start at a density of 10^6 g/cm^2 . The initial ratio of thermal to gravitational energy (α) is ~ 0.33 and we include some turbulence (Mach number of ~ 1) and solid body rotation with a energy ratio $\beta = 0.02$. Simulations are performed with both 2.5×10^7 and 2.5×10^6 SPH particles. The sink particles have accretion radii of 0.4 AU and their gravitational interactions with other sinks and the gas particles are also softened to this radius.





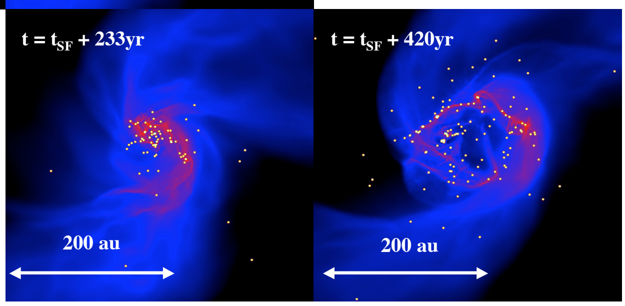


Figure 2: Column density snapshots from our 25,000,000 SPH particle simulation of the $Z = 10^{-5}\ Z_{SUN}$ EOS. The colour table is stretched over 4 orders of magnitude in column density, ranging from 100 to 10^6 g/cm^2. First, one sees the formation of a single star (3rd panel), and then, after a few local free-fall times, cool gas falls into a disc-like structure which undergoes vigorous fragmentation to form a dense cluster.

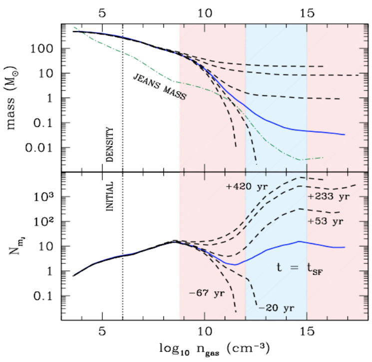


Figure 3: Distribution of masses and Jeans masses in the $Z = 10^{-5}\ Z_{SUN}$ (hi-res) simulation. The pink and blue regions denote the rapid heating and cooling phases of the EOS respectively. One can see how the first collapsing core only has a few Jeans masses at the point of star formation, but as the surrounding gas enters the cooling phase, the number of Jeans masses rises rapidly, allowing the gas to fragement at very high densities. **Note the time between the first and second stars to form is over 2 local free-fall times: without the inclusion of sink particles, we would have missed the formation of the cluster entirely.**

Results

Our calculations demonstrate that the dust-cooling model of Omukai et al (2005) can indeed lead to the formation of low-mass objects from gas with very low metallicity (see Figure 4). Further, we find that the transition from high-mass primordial stars to Population II stars with a more "normal" mass spectrum occurs early in the universe, at metallicities at or below $Z = 10^{-5}\ Z_{SUN}$. Low mass objects are also present in our primodial gas simulations, but it is unclear whether they will remain at low masses, given the extent of the available gas reservoir. The discovery of low-metallicity, low-mass, stars would be a critical test for our model of the formation of the first star cluster. Hints of its validity come from the extremely low metallicity sub-giant stars that have recently been discovered in the Galactic halo (Christlieb et al 2002; Beers & Christlieb 2005), which have iron abundances less than 10^{-5} times the solar value and masses below one solar mass, consistent with the range reported here.

Increasing Metallicity

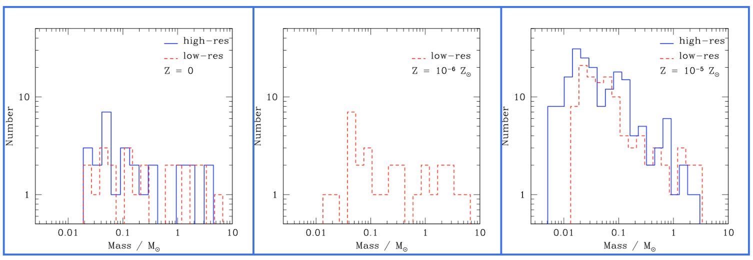


Figure 4: The mass functions from the simulations taken after 19 M_{SUN} of gas has been accreted onto the protostars.