

1. Star Formation At Low Metallicity

1.1. The Baryons Collapse Within the Halos

The dark matter is collisionless and dominates the total mass (hence gravity), so its collapse proceeds without pressure effects. But pressure must be included when considering the collapse of baryons within a dark matter halo. We assume the dark matter has already collapsed and virialized at redshift z_{vir} , with a radial density profile of the dark matter of the form calculated by Navarro, Frenk and White. This produces a gravitational potential $\phi(r)$ inside the dark matter object. We need to calculate the resulting gas distribution, ignoring cooling.

At $z < 100$ the gas temperature is decoupled from the CMB, and its pressure evolves adiabatically. Assuming the gas obeys the condition of hydrostatic equilibrium within the halo, we find

$$\frac{\rho_b}{\langle \rho_b \rangle} = \left(1 - \frac{2}{5} \frac{\mu m_p \phi}{k \langle T \rangle}\right)^{3/2}$$

where the mean temperature $\langle T \rangle$ refers to the background gas temperature and is $\mu m_p/k$. Setting $T_{vir} = -\frac{1}{3} m_p \phi/k$ as the virial temperature for the gravitational potential depth $-\phi$, the overdensity of baryons at the virialization redshift is

$$\delta_b = \frac{\rho_b}{\langle \rho_b \rangle} - 1 = \left[1 + \frac{6}{5} \frac{T_{vir}}{\langle T \rangle}\right]^{3/2} - 1.$$

If we require $\delta_b > 100$ (see §1.3 of the notes on cosmology and dark matter halos for a justification of this choice), then $T_{vir} > 17.2 \langle T \rangle$. For $z \lesssim 160$, $\langle T \rangle \approx 170[(1+z)/100]^2$ K. So the required overdensity of baryons is achieved only within halos where $T_{vir} > 3 \times 10^3[(1+z)/100^2]$ K, which defines a minimum mass for

baryonic objects of

$$M_{min} = 5 \times 10^3 \left[\frac{\Omega_m h^2}{0.15} \right]^{-1/2} \left[\frac{\Omega_b h^2}{0.022} \right]^{-3/5} \left[\frac{1+z}{10} \right]^{3/2} M_\odot \approx 5 \times 10^3 \left[\frac{1+z}{10} \right]^{3/2} M_\odot$$

This minimum mass is quite close to the naive Jeans mass calculation from linear theory given above.

1.2. Cooling of 0Z Gas

For solar metallicity gas, although the “metals” are only 2% of the total, it is the metals that generate dust, molecules, and cooling via atomic lines at temperatures below 10,000 K, below which H is mostly neutral. The metals control the gas thermodynamics. Normally the timescale for thermal equilibrium is much shorter than typical dynamical timescales, and hence the equilibrium temperature is set at that of cold, dense clouds, which is about 10 K. In effect, the gas self-regulates and is isothermal.

However, primordial gas has no “metals”, and therefore cannot cool effectively once H recombines. Neutral H and He have few energy levels, all those of H are many eV above the ground state, and hence offer few possibilities for line radiation. They are very poor radiators for $T < 10^4$ K, and unless some other cooling mechanism enters, the cloud would contract adiabatically. If this happens, the adiabatic index of the gas is big enough so that a pressure gradient develops which halts the gravitational collapse; the cloud is subsequently virialized, and then evolves slowly within the long cooling time scale.

Cooling at 0Z at any temperature involves the following processes: radiative recombinations, collisional ionizations where the thermal energy of the electron is converted into ionizing the atom, bound-bound transitions which become rare below 10^{-4} K as 9 eV

is required to excite the $n = 2$ level of H, and bremsstrahlung emission (radiation due to acceleration of a charge in the Coulomb field of another charge).

The cooling rate is parameterized by $\Lambda(T)/n_H^2$. In Ay 121 the rates of these various processes were examined. At $T > 10^{5.5}$ K, bremsstrahlung dominates. For $10^3 < T < 10^{5.5}$ K, collisional excitation of H and He dominate. Below 10^4 K, the cooling rate for 0Z gas drops very rapidly.

We consider the cooling time to be $t_c = 3\pi/[2n\Lambda(T)]$, where n is the total number density for the gas. The free-fall time is $t_{ff} = \sqrt{32G\rho/(3\pi)}$, and the Hubble time is also relevant, $t_H = H(z)^{-1}$.

Thus the sharp drop in the cooling rate for $T < 10^4$ K for 0Z gas causes the collapse time to increase substantially, in effect preventing the collapse of primordial gas clouds.

Below 10^4 K, we must turn to cooling by H_2 , which can make a major contribution to the cooling rate even though the ratio of H_2/H is very low, and even though H_2 molecules have no dipole moment. Another consequence of relying on H_2 for cooling is that the cloud does not become optically thick until densities much higher than would occur in a solar metallicity gas cloud of the same mass, so at least initially the gas is optically thin. The detailed cooling rates depend on the population of the low vibrational and rotational levels of the molecule by collisional excitation; the deexcitation rates contain terms from both collisional and radiative interactions.

The critical density is that at which the collisional excitation rate equals that of the radiative decay rate, for H_2 it is about $10^4/\text{cm}^3$ for the lowest rotational transition. The number density of H_2 molecules $\propto n^2(H)$ at low density with respect to the critical density and to $n(H)$ at high density, while the emissivity is proportional to the number density of molecules and to the radiative deexcitation rate. Detailed calculations are required to take

into account additional terms from dissociation of the molecules etc.

Molecules normally form on the surface of dust grains. Since there is no dust at 0Z, the molecules must form in the gas, which is much harder to do. A detailed consideration of the various reactions involved is required to evaluate the ratio of $n(\text{H})/n(\text{H}_2)$. The relevant reactions require free electrons, which can only come from relics of ionization after the epoch of recombination. Eventually after the recombination time exceeds the Hubble time, the electron fraction remains fixed (“freezes out”); this occurs at $z \sim 70$. After that, in the absence of metals, this fraction is about 10^{-6} , which is not enough to produce much cooling, and the virial temperature of objects which can cool is not decreased much below 10,000 K.

To get enough cooling, we need this fraction to be about 10^{-3} . This occurs as a result of the collapse of dark matter structures, with the baryons following along later. The fraction of H_2 is then boosted to the necessary level. Detailed calculations must include e, H, H^+ , H^- , H_2 , and H_2^+ , and are rather complex.

The results of such calculations delineate the regime of T and redshift at which objects can cool ($t_c \ll t_{ff}$). Calculations with a full set of the above species and reaction rates suggest that H_2 cooling allows 3σ fluctuations at $z \sim 30$ to collapse. These correspond to halos with virial temperature of about 3000 K. Adding HD to the mix, even though it has a very low fractional abundance, helps a lot, as HD does have a dipole moment, and its lowest energy transition $\Delta E/k$ corresponds to 128 K, while that of H_2 is 510 K. Thus if HD cooling is effective, the gas will cool to ~ 100 K. Calculations suggest that it is possible through shocks to create the requisite amount of HD to allow cooling of 0Z gas at $z > 10$ to the temperature of the CMB. This would allow the formation of lower mass stars in a second generation; the high luminosity of the first generation of massive stars is needed to give rise to the shocks to produce HD in 0Z gas.

The minimum metallicity at which heavy elements can provide enough cooling to have

a more normal mode of star formation marking the transition between 0Z and normal collapse and fragmentation of a gas cloud can be calculated from cooling curves and is about $10^{-4} Z_{\odot}$ (assuming Solar abundance ratios among the heavy elements). Cooling is then driven primarily from line emission from CI, OI, and CO. Other heavy elements, which are much less abundant under the assumption of solar abundance ratios, make only minor contributions to the cooling. The presence of metals enables fragmentation down to smaller mass scales, and also complicates the determination of the mass of the star formed from the mass of the collapsing fragment by halting the accretion through radiation pressure onto the dust.

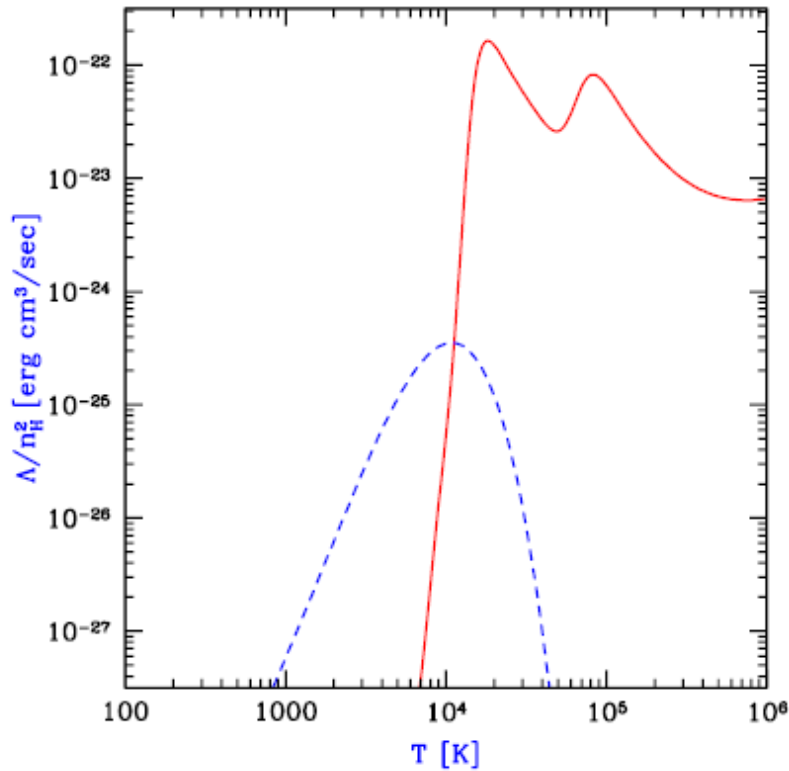


Fig. 12.— Cooling rates as a function of temperature for a primordial gas composed of atomic hydrogen and helium, as well as molecular hydrogen, in the absence of any external radiation. We assume a hydrogen number density $n_H = 0.045 \text{ cm}^{-3}$, corresponding to the mean density of virialized halos at $z = 10$. The plotted quantity Λ/n_H^2 is roughly independent of density (unless $n_H \gg 10 \text{ cm}^{-3}$), where Λ is the volume cooling rate (in $\text{erg}/\text{sec}/\text{cm}^3$). The solid line shows the cooling curve for an atomic gas, with the characteristic peaks due to collisional excitation of H I and He II. The dashed line (calculated using the code of Abel available at <http://logy.harvard.edu/tabel/PGas/cool.htm>) shows the additional contribution of molecular cooling, assuming a molecular abundance equal to 0.1% of n_H .

Fig. 1.— Fig. 12 from Barkana & Loeb, 2001.

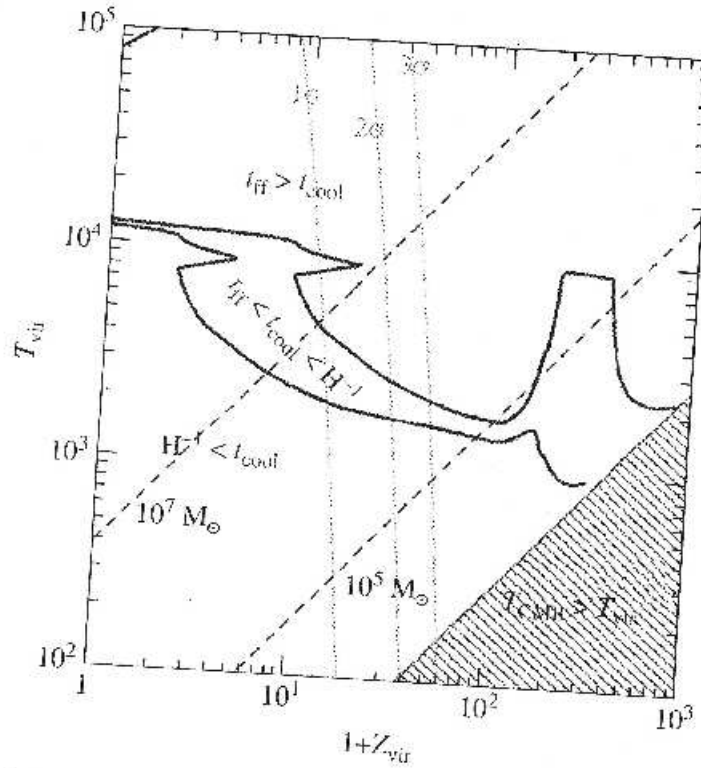


Fig. 2. Cooling diagram. The two thick *solid lines* divide the plane into three regions. The lower right region is forbidden from cooling, due to CMB Compton heating. *Dashed lines* denote loci of constant given mass. Also shown are 1σ , 2σ , 3σ fluctuations of the primordial density field for a concordance Λ CDM cosmological model

Fig. 2.— Objects cool when $t_c \ll t_{ff} < H^{-1}$, where t_c is the cooling time, t_{ff} is the free fall time, H^{-1} is the expansion timescale of the universe. The lower right shaded area corresponds to regions where $T_{CMB} > T_{vir}$, the virial temperature. Such regions cannot cool at all irrespective of the particular cooling mechanism being considered. The lower left has $H^{-1} < t_c$; cooling is impossible there as it takes more than a Hubble time to cool. The large upper region can cool. (Fig. 2 from Ferrara’s article in *First Stars*.)

1.3. Fragmentation of the Gas Into Stars

After its birth, the protostar grows within the dark matter halo by accretion of the large reservoir of surrounding gas. The mass accretion rate is determined by the density distribution of gas around the protostar, which is a function of the prestellar temperature. The mass of the forming star is set by the time when the accretion stops. Initially the protostar is cool, and its interior opacity is dominated by free-free absorption. Its luminosity is low, and hence the timescale for cooling the protostellar interior (i.e. the Kelvin-Helmholtz time, given by the internal energy/ L) is long. Thus the accreted material piles onto the star without further cooling, the protostar mass increases, and thus its interior temperature increases. Once the interior temperature becomes high enough, the opacity falls rapidly, the protostar’s luminosity rises, and the Kelvin-Helmholtz time decreases. Eventually a self-regulating mechanism develops to keep to match the accretion timescale to τ_{KH} . Some nuclear reactions begin in the core, but not enough to provide the necessary luminosity, so the protostar continues contracting. Eventually the core becomes hot enough to synthesize carbon, ignite the CNO cycle, and the star has reached the massive star 0Z main sequence and is stable. If the accretion rate is very high, the protostar can reach the Eddington limit luminosity before H ignition, and this may lead to an explosion, the loss of the surface layers, etc.

The main feature of 0Z protostar evolution is that without metals radiation pressure cannot stop the accretion, which can continue at a moderate rate for a long time.

While the collapse of the gas is a well posed physics problem with well specified initial conditions, for a given set of primordial density fluctuations, subsequent fragmentation is no longer tractable analytically, and one must proceed to numerical simulations incorporating the relevant physics. A crucial issue is calculating the detailed properties of the cooling of low metallicity gas as described above.

The key simulations are by the groups led by Volker Bromm and by Tom Abel, and were first carried out within the past decade. Initial results suggested that typical masses of the first stars are 100 to 1000 M_{\odot} , much higher than is normal for the solar neighborhood at the present time.

To take into account the non-uniform density, as the fragment is located within a collapsing gas cloud, we need the Bonnor-Ebert limiting mass instead of the Jeans mass. This has the same functional form as the Jeans mass, with a slightly different multiplicative constant; the former gives a slightly larger critical mass for collapse. The Bonner-Ebert mass (see Bonner, 1956, MNRAS, 116, 351) is the largest mass that an isothermal gas sphere embedded in a medium of constant pressure can have while still maintaining hydrostatic equilibrium. If $M > M_{BE}$, gravitational collapse will occur. $M_{BE} = (c_{BE}c_s^4)/(P_0^{1/2}G^{3/2})$, where the dimensionless constant c_{BE} is ~ 1.18 and c_s is the isothermal sound speed.

Once the first star in a halo “turns on”, the feedback from its radiative luminosity will halt the accretion of further mass onto it. If the halo has a virial temperature lower than that of photoionized gas (10,000 K), the ignition of a single star may ionize all the gas, and the halo will probably then dissolve.

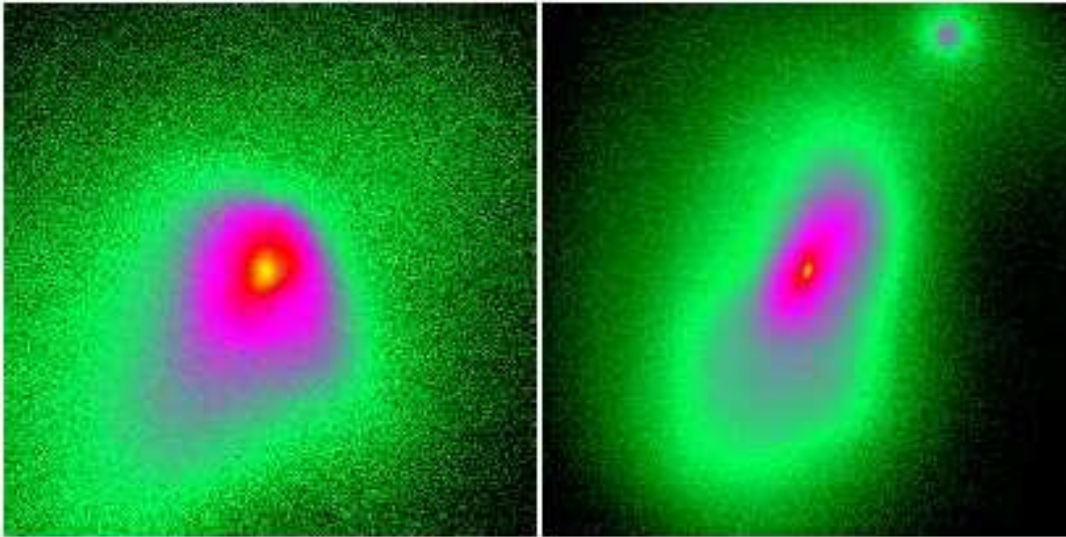


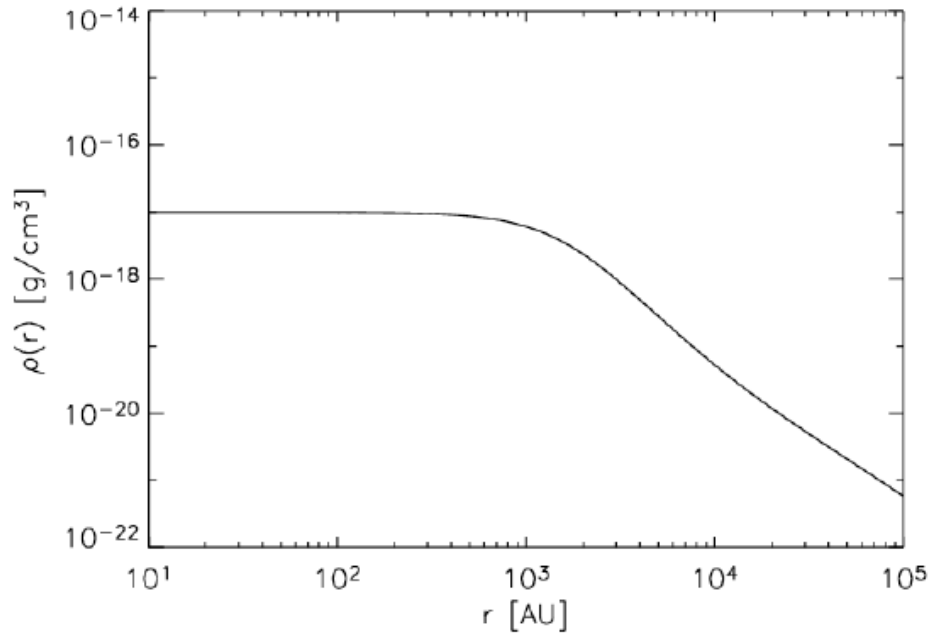
Fig. 2. Collapse and fragmentation of a primordial cloud (from Bromm & Loeb 2004). Shown is the projected gas density at a redshift $z \simeq 21.5$, briefly after gravitational runaway collapse has commenced in the center of the cloud. *Left:* The coarse-grained morphology in a box with linear physical size of 23.5 pc. At this time in the unrefined simulation, a high-density clump (sink particle) has formed with an initial mass of $\sim 10^3 M_{\odot}$. *Right:* The refined morphology in a box with linear physical size of 0.5 pc. The central density peak, vigorously gaining mass by accretion, is accompanied by a secondary clump.

Fig. 3.— from Bromm & Loeb, 2004, *New Astronomy*, 9, 353

Hydrostatic self-gravitating spheres

Numerical solutions:

Plotted logarithmically
(which we will usually
do from now on)



Bonnor-Ebert Sphere

Fig. 4.— from class notes on star formation,
www.mpia-hd.mpg.de/home/dullemon/lectures/starplanet/index.html.

1.4. The IMF for 0Z Stars

What is the IMF for 0Z stars in collapsing halos ? Is it the Salpeter function ($dn/dM \propto M^{-2.35}$) or is it biased towards much more massive stars ? Does a single clump (proto-halo) produce a single massive star with no fragmentation ? If it is biased towards higher masses, why are the remnants from PISN so hard to detect (i.e. very strong odd/even effect in abundance ratios) ? If not so biased, why have we not found Pop III stars today in the Milky Way halo ? A bias towards high mass comes from limited fragmentation of cloud at 0Z due to problems with cooling. As described above, the expected typical stellar mass from 0Z first generation of stars was $M > 100 M_{\odot}$ in work until 5 years ago (i.e. the first simulations by the Bromm and Abel groups). But detailed chemical abundance analyses of extremely metal-poor stars in the halo of the Milky Way together with the PISN problem have pushed us to desire an IMF with lower mass stars dominating. Maybe it is possible to hide PISN ejecta by dilution with ejecta from Pop II.5 in some way ?

Suggested reading:

- a) First Light, chapter by A. Loeb and by A. Ferrara
- b) review of first stars, Bromm & Larson, 2004, ARAA, 42, 79
- c) Evolution of massive stars along cosmic history, Meynet, Ekstrom, 2008, A&A, 478, 467 and more recent conference contributions, see especially proceedings of IAU Symposium 250, Massive Stars as Cosmic Engines.
- d) Heger, Fryer, Woosley, Langer, Hartmann, 2003, ApJ, 591, 288 stellar death channels for non-rotating massive single stars
- e) A. Loeb, 2007, “The Frontier of Reionization: Theory and Forthcoming Observations”, Astro-ph:0711.3463
- f) R. Barkana & A. Loeb, 2001, “In the Beginning: The First Sources of Light and Reionization in the Universe”, see Astro-ph:00104683