Protostellar Feedback Processes and the Mass of the First Stars

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Abstract. We review theoretical models of Population III.1 star formation, focusing on the protostellar feedback processes that are expected to terminate accretion and thus set the mass of these stars. We discuss how dark matter annihilation may modify this standard feedback scenario. Then, under the assumption that dark matter annihilation is unimportant, we predict the mass of stars forming in 12 cosmological minihalos produced in independent numerical simulations. This allows us to make a simple estimate of the Pop III.1 initial mass function and how it may evolve with redshift.

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INTRODUCTION

The first stars laid the foundations for galaxy formation. As described below, we expect that these Population III.1 stars, i.e. having negligiblemetallicity and experiencing negligible influence from other astrophysical sources external to their minihalos, were massive and thus injected significant radiative, mechanical and chemical feedback into their surroundings. We need to understand the processes that set the mass of these stars in order to have a complete theory of galaxy formation and evolution. Supermassive black holes reside in the centers of most large galaxies and some massive examples have been seen at very early times [1, 2]. The remnants of the first stars may have been the seeds of these black holes.

We first review the accretion and feedback processes that are expected to occur during the birth of Pop III.1 stars. We emphasize some of the uncertainties in existing models. We then describe preliminary work applying these models to a population of Pop III.1 minihalos in order to predict the initial mass function (IMF) of the stars they produce.

ACCRETION AND FEEDBACK PROCESSES

Here we give a brief outline of these processes, which have been reviewed in more detail by Tan & McKee[3]. Small dark matter halos grow and merge together to eventually form $\sim 10^6 M_\odot$ “mini-halos” by redshifts $z \sim 30 – 20$. Baryons collect in these halos and cool down to $\sim 200$ K due to the presence of trace amounts of H$_2$, the formation of which is catalyzed by small concentrations of free electrons via the H$^-$ channel. The baryons start to dominate the mass density in the innermost $\sim 1$ parsec. Above
the critical density of $n_H \sim 10^4 \text{ cm}^{-3}$, cooling is inefficient, contraction is slow and subsonic, and the temperature gradually rises towards the center. The gas develops a self-similar, power law density structure with $\rho \propto r^{-2.2}$, i.e. slightly steeper than a singular, isothermal sphere. When the central density exceeds $\sim 10^{10} \text{ cm}^{-3}$, the gas becomes fully molecular via the 3-body formation channel, cooling is much more efficient and dynamical collapse is initiated from the inside-out.

An analytic estimate of the accretion rate to the central star+disk system is [4]:

$$m_{sd} = 0.026 \varepsilon_{sd} K'^{15/7} (M/M_\odot)^{-3/7} M_\odot \text{ yr}^{-1},$$

(1)

where $M$ is the mass originally enclosed by the currently accreting mass shell, $\varepsilon_{sd}$ is the instantaneous star formation efficiency, and $K'$ is the “entropy parameter” normalizing the polytropic description of the initial core, $P = K \rho \gamma$ with $\gamma \approx 1.1$, and is defined as

$$K' = \frac{P/\rho \gamma}{1.88 \times 10^{12} \text{ cgs}} = \frac{T_{\text{eff}}'}{300 \text{ K}} \left(\frac{10^4 \text{ cm}^{-3}}{n_H}\right)^{0.1},$$

(2)

where $T_{\text{eff}}'$ is an effective temperature that includes the modest effect of subsonic turbulent motions that are seen in the numerical simulations of Abel, Bryan & Norman[5].

The gas core has significant rotational motions[5] and so a disk should form inside the sonic point of the accretion flow. We expect the disk mass to build up until gravitational instabilities produce spiral density waves and other structures that allow transfer of mass inwards and angular momentum outwards through the disk. For fiducial accretion rates and disk sizes, we expect the optically thick region of the disk to be stable to gravitational fragmentation[6]. Most simulations of Pop III.1 star formation appear to produce single stars[7], although these have followed only the earliest stages of accretion when the central protostar has yet to accrete most of its expected final mass.

The accretion disk is the first place where turbulent eddies have time to amplify significantly seed magnetic field produced by the Biermann battery mechanism during the formation of the halo[6]. If such an accretion disk dynamo produces large-scale, dynamically-strong B-fields, then a bipolar magneto-centrifugally-driven outflow will be launched, which can reduce $\varepsilon_{sd}$. Tan & Blackman[6] estimated $\varepsilon_{sd} \approx 0.5$ by the time $m_\star \sim 200M_\odot$, which is not as important as radiative feedback in the fiducial case with $K' = 1$ (see below).

Matter joins the protostar via an accretion boundary layer shock and the internal energy of the gas that is advected into the protostar is set by the properties of this shock, the accretion rate and the amount of energy that is radiated. The internal energy of the accreted gas in turn helps set the size of the protostar[8, 4].

Weakly interacting massive particle (WIMP) dark matter may self-annihilate and provide significant energy input into the protostar[9, 10], stabilizing its initial radius at $\sim 10 \text{ AU}$, rather than $\sim 0.1 \text{ AU}$ in the fiducial case. The subsequent evolution is uncertain[11], but contraction to the main sequence may be delayed with respect to the fiducial case without such support (see below), affecting the mass scale at which radiative feedback truncates accretion. Uncertainties include the assumed central density profile of dark matter and how this may be affected by supersonic baryonic infall and disk accretion, including heating by spiral density waves. For the remainder of this article, we consider the case of negligible WIMP annihilation heating.
The protostellar evolution can be followed given knowledge of the accretion rate\cite{4,12}. Once the protostar is older than its local Kelvin-Helmholtz time, it starts contracting towards the main sequence, typically settling there by $\sim 100\, M_\odot$. The star could continue to accrete in this state if feedback is not strong enough to reverse accretion. Given the accretion rates of equation (1) and stellar evolution timescales of Schaerer\cite{13}, the maximum accreted stellar mass before supernova explosion is $m_{*,\text{max}}\simeq 1900K^{1.28}M_\odot$\cite{14}.

McKee & Tan\cite{14} considered a number of feedback processes that will intervene before a supernova occurs. Destruction of H$_2$ coolant in the minihalo by FUV photons was not found to reduce the accretion rate to the star significantly, since by the time this occurs the protostar has already developed a potential well deep enough for atomic cooling to allow accretion. Lyman-$\alpha$ radiation pressure was also found to be ineffective since it requires multiple scatterings to build up dynamically important pressures, but this leads to diffusion and escape of the photons along bipolar cavities.

Direct ionization of the accretion flow to create a $\sim 25,000$ K HII region whose high thermal pressure can reverse accretion is the first important feedback process, occurring by $\sim 50\, M_\odot$ in the fiducial case. The HII region quickly breaks out in all directions above and below the disk, reducing $\varepsilon_{\text{rd}}$ by factors of several. By the time $m_* = 100\, M_\odot$ the accretion rate from disk-shielded directions is about a factor of 10 smaller than in the no-feedback case. These estimates use a 1D model for the disk vertical thickness and assume gas from disk-shielded directions accretes as it would in the absence of feedback. The protostar ionizes the accretion disk atmosphere, which redirects some ionizing flux to outer parts of the disk that are neutral. An ionized, “photoevaporative” flow develops from these outer regions with mass-loss rate\cite{15}

$$\dot{m}_{\text{evap}} \simeq 4.1 \times 10^{-5} S_{49}^{1/2} T_4^{0.4} m_{*,2}^{1/2} \, M_\odot \, \text{yr}^{-1},$$

where $S_{49}$ is the H-ionizing photon luminosity in units of $10^{49}$ photons s$^{-1}$, $T_4$ is the ionized gas temperature in units of $10^4$ K, and the star+disk mass has been normalized to $100\, M_\odot$. This analytic estimate has not yet been confirmed by numerical simulation.

The final accreted mass, $m_{*,f}$, is estimated by the condition $\dot{m}_{\text{evap}} = \dot{m}_{*,d}$, yielding\cite{14}:

$$m_{*,f} = 145 K^{60/47} (2.5/T_4)^{0.24} (f_{\text{sh}}/0.2)^{28/47} (\bar{\varepsilon}_{\text{rd}}/0.25)^{12/47} M_\odot,$$

where $f_{\text{sh}}$ is the shadowing factor, i.e. fraction of the sky seen from the protostar blocked by the disk, and $\bar{\varepsilon}_{\text{rd}}$ is the mass-averaged value of $\varepsilon_{\text{rd}}$ over the formation of the star. The fiducial normalizations of these parameters were derived from calculations of the protostellar and accretion disk evolution coupled with the effects of ionizing feedback. The predicted mass of Pop III.1 stars in the fiducial case is $\sim 150\, M_\odot$. The strongest parameter dependence is with $K'$, i.e. via the accretion rate. High accretion rate protostars reach higher masses because photoevaporative truncation occurs at a higher mass, partly because contraction to the main sequence and HII region breakout were delayed, thus raising $\bar{\varepsilon}_{\text{rd}}$, and partly because the star must produce more ionizing photons to increase photoevaporative mass-loss to counter the higher accretion rate.

A number of factors are likely to raise this estimate of the final accreted mass, including instabilities during the breakout of the HII region and rotation of the protostar that reduces the equatorial flux of ionizing photons and thus the photoevaporative mass-loss.
THE POP III.1 IMF

O’Shea & Norman [16] studied the properties of Pop III.1 pre-stellar cores as a function of redshift. They found that cores at higher redshift are hotter in their outer regions, have higher free electron fractions and so form larger amounts of H$_2$ (via H$^-$), although these are always small fractions of the total mass. As the centers of the cores contract above the critical density of $10^4$ cm$^{-3}$, those with higher H$_2$ fractions are able to cool more effectively and thus maintain lower temperatures to the point of protostar formation. The protostar thus accretes from lower-temperature gas and the accretion rates, proportional to $c_s^3 \propto T^{3/2}$, are smaller. Measuring infall rates at the time of protostar formation at the scale of $M = 100 M_\odot$, O’Shea & Norman found accretion rates of $\sim 10^{-4} M_\odot$ yr$^{-1}$ at $z = 30$, rising to $\sim 2 \times 10^{-2} M_\odot$ yr$^{-1}$ at $z = 20$. They used these accretion rates to estimate the mass of the star that forms by finding the condition of when the accretion timescale was equal to the Kelvin-Helmholtz timescale, thus predicting an increase in the typical Pop III.1 stellar mass as $z$ decreases over this range.

Here we present preliminary results of a more detailed estimate of the Pop III.1 stellar masses that result from these cores. First we estimate the expected protostellar accretion rates in the O’Shea & Norman[16] cores (Fig. 1). In the simulations, the inner regions have not yet reached the densities associated with dynamical collapse, so the observed mass infall rate underestimates the expected accretion rates. Thus, we assume the solution describing the collapse of a singular polytropic sphere (SPS)[4] holds for the inner mass shells. We derive this by evaluating the interior mass averaged SPS solution [17] used in eq. 1 the accretion rate increases from $\propto T$ at large radii ($r \gg c_s t$, where $t = 0$ is the moment of protostar formation) to $2.58 c_s^3 / G$ at small radii, an increase of a factor 3.7. Thus we increase the observed infall mass flux by this factor, and refer to this as the “enhanced infall rate”. Beyond the mass shell where this mass accretion rate becomes larger than that predicted by the collapse of the SPS, we assume the accretion rate is equal to their geometric mean. This is designed to approximate the transition from the SPS solution to the infall solution. In the outer parts of the core, the gas has not yet virialized, $K'$ becomes large and the SPS-based accretion rate becomes unrealistically large, exceeding the enhanced infall rate. In this case, we adopt only the enhanced infall rate as the estimate of the mass accretion rate.

We then estimate the final protostellar mass, $m_{*,f}$, using the feedback models of McKee & Tan[14]. The collapsed mass at HII region breakout can be evaluated from their eq. (41) with parameters: $\phi_{\text{Edd}} = 0.3$, $\mu = 1/\sqrt{2}$, $f_d = 1/3$, $\phi_S = 1$, $T_4 = 2.5$, $f_{\text{Kep}} = 0.5$, $r_{\text{HII}} = 2 r_g$ and $\epsilon_{sd} = 1$, then $m_{*,\text{break}} = 48.4 K'^{25/14} M_\odot = 6.12 m_{sd,-3}^{35/27} M_\odot$. Following the accretion history of each halo, we assume that once this condition is met HII region breakout is fast and $m_{sd}$ is immediately reduced by the disk shadowing factor $f_{\text{sh}} = 0.2$. Finally, we calculate when disk photoevaporation overwhelms accretion, i.e. $m_{\text{evap}} \rightarrow 1.96 \times 10^{-4} m_{*,f}^{5/4} M_\odot$ yr$^{-1} > m_{sd}[14]$, at which point we assume the protostar has reached its $m_{*,f}$. A more detailed analysis, fully coupling $m_{sd}$ to these protostellar evolution and feedback models will be presented in a future paper.

Figure 2 shows the derived final protostellar masses as a function of the collapse
FIGURE 1. Estimates of mass accretion rates of the 12 Pop III.1 cores of O’Shea & Norman[16], each indicated by a different line style and color, with fiducial rate of Tan & McKee[4] (eq. 1) shown by the black dot-dashed line: (a) Top left: Accretion rate based on SPS collapse with $K'$ profiles (averaged over interior mass) (eq. 1); (b) Top right: Accretion rate based on mass flux through spherical shells at the end of the simulations; (c) Bottom left: Accretion rate as in (b), now smoothing at 50% weight with the two adjacent mass shells and an enhancement by a factor of 3.7 as expected if the Hunter[17] solution holds; (d) Bottom right: Final adopted accretion rate, assuming inner SPS solution (a), then geometric mean of the (a) and (c) results when the latter starts to dominate, then (c) if (a) starts to exceed (c) again (see text).

There is a weak trend for lower-mass stars to be formed at higher redshift due to lower accretion rates, as suggested by O’Shea & Norman[16]. However, there is significant dispersion about this trend, since although the high $z$ protostars do initially have low accretion rates, these can increase due to large mass infall rates at the mass shells for $M \sim 100 - 1000 M_\odot$. Figure 2 also shows the distribution of the initial Pop III.1 stellar masses, i.e. their IMF, based on these 12 minihalos. These are the first halos to collapse in their local cosmological volumes, so may be a biased
sample. The sample is also small, so we note only some basic features: we see very few stars below $80 \, M_\odot$, a steep rise in the IMF around $100 \, M_\odot$, then a general decline to higher masses, with the most massive star being $\sim 600 \, M_\odot$. The mean mass is $\sim 250 \, M_\odot$, the median is $\sim 215 \, M_\odot$ and the dispersion is $\sim 160 \, M_\odot$.

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REFERENCES

1. X. Fan, M. A. Strauss, Schneider, D. P. et al., AJ, 125, 1649–1659 (2003).
2. C. J. Willott, R. J. McLure, and M. J. Jarvis, ApJ, 587, L15–L18 (2003).
3. J. C. Tan, and C. F. McKee, in First Stars III, AIP Conf. Proc. 990, 47–62 (2008).
4. J. C. Tan, and C. F. McKee, ApJ, 603, 383–400 (2004).
5. T. Abel, G. L. Bryan, and M. L. Norman, Science, 295, 93–98 (2002).
6. J. C. Tan, and E. G. Blackman, ApJ, 603, 401-413 (2004).
7. Turk, M. J., Abel, T., and O’Shea, B. Science, 325, 601– (2009).
8. S. W. Stahler, F. Palla, & E. E. Salpeter, ApJ, 302, 590–605 (1986).
9. D. Spolyar, K. Freese, & P. Gondolo, PRL, 100, 051101– (2008).
10. A. Natarajan, J. C. Tan, and B. W. O’Shea, ApJ, 692, 692-574 (2009).
11. D. Spolyar, P. Bodenheimer, K. Freese, & P. Gondolo, ApJ, 705, 1031–1042 (2009).
12. T. Hosokawa and K. Omukai, ApJ, 703, 1810–1818 (2009).
13. D. Schaerer, A&A, 382, 28–42 (2002).
14. C. F. McKee, and J. C. Tan, ApJ, 681, 771–797 (2008).
15. D. Hollenbach, D. Johnstone, S. Lizano, F. Shu, ApJ, 428, 654–669 (1994).
16. B. W. O’Shea, and M. L. Norman, ApJ, 654, 66–92 (2007).
17. C. Hunter, C. ApJ, 218, 834–845 (1977).