Low-Metallicity Star Formation:
From the First Stars to Dwarf Galaxies
Proceedings IAU Symposium No. 255, 2008
L.K. Hunt, S. Madden & R. Schneider, eds.

doi:10.1017/S174392130802454X

Population III.1 stars: formation, feedback and evolution of the IMF

Jonathan C. Tan[1]

[1]Dept. of Astronomy, University of Florida, Gainesville, FL 32611, USA
email: jt@astro.ufl.edu

Abstract. I discuss current theoretical expectations of how primordial, Pop III.1 stars form. Lack of direct observational constraints makes this a challenging task. In particular predicting the mass of these stars requires solving a series of problems, which all affect, perhaps drastically, the final outcome. While there is general agreement on the initial conditions, H_2-cooled gas at the center of dark matter minihalos, the subsequent evolution is more uncertain. In particular, I describe the potential effects of dark matter annihilation heating, fragmentation within the minihalo, magnetic field amplification, and protostellar ionizing feedback. After these considerations, one expects that the first stars are massive $\gtrsim 100\,M_\odot$, with dark matter annihilation heating having the potential to raise this scale by large factors. Higher accretion rates in later-forming minihalos may cause the Pop III.1 initial mass function to evolve to higher masses.

Keywords. stars: formation, galaxies: formation, dark matter, cosmology: theory

1. Introduction: The Importance of Pop III.1 Stars and their IMF

The first, essentially metal-free (i.e. Population III), stars are expected to have played a crucial role in bringing the universe out of the dark ages: initiating the reionization process, including the local effects of their H II regions in generating shocks and promoting formation of molecular coolants in the relic phase; photodissociating molecules; amplifying magnetic fields to possibly dynamically important strengths; and generating the mechanical feedback, heavy elements and possible neutron star or black hole remnants associated with supernovae. In these ways Pop III stars laid the foundations for galaxy formation, including supermassive black holes and globular clusters. Many of these processes are theorized to depend sensitively on the initial mass function (IMF) of Pop III stars, thus motivating its study. The formation of the first Pop III stars in a given region of the universe is expected to have been unaffected by other astrophysical sources and these have been termed Pop III.1, in contrast to Pop III.2 (McKee & Tan 2008, hereafter MT08). Pop III.1 are important for influencing the initial conditions for future structure formation and for having their properties determined solely by cosmology. There is also the possibility, described in Sect. 2.1, that Pop III.1 star formation may be sensitive to the properties of weakly interacting massive particle (WIMP) dark matter.

Unfortunately, at the present time and in the near future we expect only indirect observational constraints on the Pop III IMF. The epoch of reionization can be constrained by CMB polarization (Page *et al.* 2007) and future high redshift 21 cm HI observations (e.g. Morales & Hewitt 2004). Metals from individual Pop III supernovae may have imprinted their abundance patterns in very low metallicity Galactic halo stars (Beers & Christlieb 2005) or in the Ly-α forest (Schaye *et al.* 2003; Norman, O'Shea, & Pascos 2004). Light from the first stars may contribute to the observed NIR background intensity, (e.g. Santos, Bromm, & Kamionkowski 2002), and its fluctuations (Kashlinsky *et al.* 2004; c.f. Thompson *et al.* 2007). If massive, supernovae marking the deaths of the first stars may be observable by JWST (Weinmann & Lilly 2005). If these supernovae produce gamma-ray bursts then these may already be making a contribution to the population observed by SWIFT (Bromm & Loeb 2002).

The lack of direct observations of Pop III star formation means theoretical models lack constraints, which is a major problem for treating such a complicated, nonlinear process. Numerical simulations have been able to start with cosmological initial conditions and advance to the point of protostar formation (see Yoshida *et al.*, these proceedings), but progressing further through the protostellar accretion phase requires additional modeling of complicated processes, including a possible need to include extra physics such as WIMP annihilation and magnetic fields. Building up a prediction of the final mass achieved by the protostar, i.e. the initial mass (function) of the star (population), is akin to building a house of cards: the reliability of the structure becomes more and more precarious.

In this article we summarize theoretical attempts to understand the formation process and resulting IMF of Pop III.1 stars. We have reviewed much of these topics previously (Tan & McKee 2008), so here we concentrate on a discussion of some of the more uncertain aspects in these models, including the potential effects of WIMP annihilation on Pop III.1 star formation, fragmentation during Pop III.1 star formation, the generation of magnetic fields, the uncertainties in predicting the IMF from feedback models, and the evolution of the Pop III.1 IMF. Note, when discussing possible fragmentation during the formation of a Pop III.1 star, we will consider all stars that result from the same minihalo to be Pop III.1, i.e. they are unaffected by astrophysical sources external to their own minihalo.

2. Initial Conditions and Possible Effects of WIMP Annihilation

The initial conditions for the formation of the first stars are thought to be relatively well understood: they are determined by the growth of small-scale gravitational instabilities from cosmological fluctuations in a cold dark matter universe. The first stars are expected to form at redshifts $z \sim 10-50$ in dark matter "minihalos" of mass $\sim 10^6\ M_\odot$ (Tegmark *et al.* 1997). In the absence of any elements heavier than helium (other than trace amounts of lithium) the chemistry and thermodynamics of the gas are very simple. Once gas collects in the relatively shallow potential wells of the minihalos, cooling is quite weak and is dominated by the ro-vibrational transitions of trace amounts of H_2 molecules that cool the gas to ~ 200 K at densities $n_{\rm H} \sim 10^4\ {\rm cm}^{-3}$ (Abel, Bryan, & Norman 2002; Bromm, Coppi, & Larson 2002). Glover *et al.* (these proceedings) review the effects of other potential coolants, finding they are small for Pop III.1 star formation.

As the gas core contracts to greater densities, the H_2 cooling becomes relatively inefficient and the temperature rises to ~ 1000 K. At densities $\sim 10^{10}\ {\rm cm}^{-3}$ rapid 3-body formation of H_2 occurs, creating a fully molecular region that can cool much more efficiently. This region starts to collapse supersonically until conditions become optically thick to the line and continuum cooling radiation, which occurs at densities $\sim 10^{17}\ {\rm cm}^{-3}$. Recent 3D numerical simulations have advanced to densities of order $10^{21}\ {\rm cm}^{-3}$ (see contribution by Yoshida *et al.*, these proceedings), but have trouble proceeding further given the short timesteps required to resolve the dynamics of the high density gas of the protostar. Further numerical progress can be achieved by introducing sink particles (Bromm & Loeb 2004) or with 1D simulations (Omukai & Nishi 1998; Ripamonti *et al.* 2002).

Alternatively, given the above initial conditions, the subsequent accretion rate to the protostar can be calculated analytically (Tan & McKee 2004, hereafter TM04). The accretion rate depends on the density structure and infall velocity of the gas core at the point when the star starts to form. Omukai & Nishi (1998) and Ripamonti *et al.* (2002) showed that the accreting gas is isentropic with an adiabatic index $\gamma \simeq 1.1$ due to H_2

https://doi.org/10.1017/S174392130802454X Published online by Cambridge University Press

cooling; i.e., each mass element satisfies the relation $P = K\rho^\gamma$ with the "entropy parameter" $K =$ const. In hydrostatic equilibrium—and therefore in a subsonic contraction—such a gas has a density profile $\rho \propto r^{-k_\rho}$ with $k_\rho \simeq 2.2$, as is seen in simulations. TM04 describe the normalization of the core density structure via the "entropy parameter"

$$K' \equiv (P/\rho^\gamma)/1.88 \times 10^{12} \text{ cgs} = (T'_{\rm eff}/300 \text{ K})(n_{\rm H}/10^4 \text{cm}^{-3})^{-0.1}, \quad (2.1)$$

where $T'_{\rm eff} \equiv T + \mu\sigma^2_{\rm turb}/k$ is an effective temperature that includes the modest effect of subsonic turbulent motions that are seen in numerical simulations (Abel *et al.* 2002).

For the infall velocity at the time of protostar formation, simulations show the gas is inflowing subsonically at about a third of the sound speed (Abel *et al.* 2002). Hunter's (1977) solution for mildly subsonic inflow (Mach number = 0.295) is the most relevant for this case. It has a density that is 1.189 times greater than a singular isothermal sphere (Shu 1977) at $t = 0$, and an accretion rate that is 2.6 times greater.

Feedback from the star, whether due to winds, photoionization, or radiation pressure, can reduce the accretion rate of the star. TM04 and MT08 define a hypothetical star+disk mass, $m_{*d,0}$, and accretion rate, $\dot{m}_{*d,0}$, in the absence of feedback. In this case, the star+disk mass equals the mass of the part of the core (out to some radius, r, that has undergone inside-out collapse) from which it was formed, $m_{*d,0} = M(r)$. The instantaneous and mean star formation efficiencies are $\epsilon_{*d} \equiv \dot{m}_{*d}/\dot{m}_{*d,0}$ and $\bar{\epsilon}_{*d} \equiv m_{*d}/m_{*d,0} = m_{*d}/M$, respectively.

Assuming the Hunter solution applies for a singular polytropic sphere with $\gamma = 1.1$, the accretion rate is then (TM04)

$$\dot{m}_{*d} = 0.026\epsilon_{*d} K'^{15/7} (M/M_\odot)^{-3/7} \ M_\odot \text{ yr}^{-1}, \quad (2.2)$$

with the stellar mass smaller than the initial enclosed core mass via $m_* \equiv m_{*d}/(1 + f_d) = \bar{\epsilon}_{*d} M/(1 + f_d)$. We choose a fiducial value of $f_d = 1/3$ appropriate for disk masses limited by enhanced viscosity due to self-gravity.

2.1. *Possible Effects of Dark Matter Annihilation*

Pop III.1 stars form at the centers of dark matter (DM) minihalos. While the mass density is dominated by baryons inside ~ 1 pc, adiabatic contraction ensures that there will still be a peak of DM density co-located with the baryonic protostar. As discussed by Spolyar *et al.* (2008), if the dark matter consists of a weakly interacting massive particle (WIMP) that self annihilates, then this could lead to extra heating that can help support the protostar against collapse. Spolyar *et al.* calculated that, depending on the dark matter density profile, WIMP mass, and annihilation cross section, the local heating rate due to dark matter could exceed the baryonic cooling rate for densities $n_{\rm H} \gtrsim 10^{14}$ cm^{-3}, corresponding to scales of about 20 AU from the center of the halo/protostar.

Natarajan, Tan, & O'Shea (2008) revisited this question by considering several minihalos formed in numerical simulations. While there was some evidence for adiabatic contraction leading to a steepening of the dark matter density profiles in the centers of the minihalos, this was not well resolved on the scales where heating may become important. Thus various power law ($\rho_\chi \propto r^{-\alpha_\chi}$) extrapolations were considered for the DM density. A value of $\alpha_\chi \simeq 1.5$ was derived based on the numerically well-resolved regions at $r \sim 1$ pc. A steeper value of $\alpha_\chi \simeq 2.0$ was derived based on the inner regions of the simulations. In the limit of very efficient adiabatic contraction, one expects the dark matter density profile to approach that of the baryons, which would yield $\alpha_\chi \simeq 2.2$. For the density profiles with $\alpha_\chi \simeq 2.0$, Natarajan *et al.* (2008) found that dark matter heating inevitably becomes dominant. Natarajan *et al.* also considered the global quasi-equilibrium structures for which the total luminosity generated by WIMP annihilation that is trapped in the protostar, $L_{\chi,0}$, equals that radiated away by the baryons, assuming both density distributions are power laws truncated at some radius, r_c, with a constant density core. This core radius was varied to obtain the equilibrium luminosity. Typical results were $L_{\chi,0} \sim 10^3\, L_\odot$ and $r_c \simeq$ to a few to a few tens of AU.

These scales at which equilibrium is established are important for determining the subsequent evolution of the protostar, which will continue to gain baryons and probably additional dark matter via adiabatic contraction. Even in the limit where no further dark matter becomes concentrated in the protostar, that which is initially present can be enough to have a major influence on the subsequent protostellar evolution. As the protostar gains baryonic mass it requires a greater luminosity for its support. If there was no dark matter heating, the protostar would begin to contract once it becomes older than its local Kelvin-Helmholz time, i.e. on timescales much longer than the stellar dynamical time. If dark matter is present, it will become concentrated as the protostar contracts, and the resulting annihilation luminosity will grow as $L_\chi \simeq L_{\chi,0}(r_*/r_{*,0})^{-3}$, assuming a homologous density profile. For a starting luminosity of $L_{\chi,0} = 1000\, L_\odot$ and radius of $r_{*,0} \simeq r_c = 10$ AU, this can mean luminosities that are easily large enough to support $\sim 100\, M_\odot$ stars, i.e. $\sim 10^6\, L_\odot$, at sizes of ~ 1 AU, i.e. much greater than their main sequence radii, which would be $\simeq 5R_\odot = 0.02$ AU. These estimates are of course very sensitive to the initial size of the protostar.

Full treatment of the protostellar evolution (see Freese *et al.* 2008 for an initial model) requires a model for the evolution of the stellar DM content, which grows by accumulation of surrounding WIMPs, but also suffers depletion due to the annihilation process. The mean depletion time in the star is $t_{\rm dep} = (\rho_\chi/\dot{\rho}_\chi) \simeq m_\chi/(\rho_\chi < \sigma_a v >) \rightarrow 105 (m_\chi/100\ {\rm GeV})(\rho_\chi/10^{12} {\rm GeV\,cm^{-3}})^{-1}$ Myr, where we have normalized to typical values of ρ_χ in the initial DM core (Natarajan *et al.* 2008). If the protostar contracts from an initial radius of 10 AU to 1 AU then $t_{\rm dep} \simeq 10^5$ yr. This becomes comparable to the growth time of the protostar (i.e. the time since its formation, its age), $t_* = 2.92 \times 10^4 K'^{-15/7} (m_*/100\, M_\odot)^{10/7}$ yr (TM04). We see that, if replenishment of WIMPs in the protostar is negligible, then depletion can become important for AU scale protostars of $\sim 100\, M_\odot$.

Protostars swollen by DM heating would have much cooler photospheres and thus smaller ionizing feedback than if they had followed standard protostellar evolution leading to contraction to the main sequence by about 100 $M_\odot$. Ionizing feedback is thought to be important in terminating accretion and thus setting the Pop III.1 IMF (MT08; see §5 below). The reduced ionizing feedback of DM-powered protostars may allow them to continue to accrete to much higher masses than would otherwise have been achieved.

3. Protostellar Accretion and Disk Fragmentation

Another process that may affect the IMF of the first stars is fragmentation of the infalling gas after the first protostar has formed. TM04 and MT08 considered the growth and evolution of the protostar in the case of no fragmentation (and no DM heating): the final mass achieved by the protostar is expected to be ~ 100–$200\, M_\odot$ and set by a balance between its ionizing feedback and its accretion rate through its disk (§5).

The accretion disk of the protostar does present an environment in which density fluctuations can grow, since there will typically be many local dynamical timescales before the gas is accreted to the star. TM04 calculated the expected disk size, $r_d(m_*)$, assuming conservation of angular momentum inside the sonic point, $r_{\rm sp}$, of the inflow,

https://doi.org/10.1017/S174392130802454X Published online by Cambridge University Press

finding

$$r_d = 1280 \left(\frac{f_{\rm Kep}}{0.5}\right)^2 \left(\frac{m_{*d,\,2}}{\bar{\epsilon}_{*d}}\right)^{9/7} K'^{-10/7}\ {\rm AU} \rightarrow 1850 \left(\frac{f_{\rm Kep}}{0.5}\right)^2 \frac{m_{*,\,2}^{9/7}}{K'^{10/7}}\ {\rm AU} \tag{3.1}$$

where $m_{*d,2} = m_{*d}/100\,M_\odot$, $m_{*,2} = m_*/100\,M_\odot$, the $\rightarrow$ is for the case with $f_d = 1/3$ and $f_{\rm Kep} \equiv v_{\rm rot}(r_{\rm sp})/v_{\rm Kep}(r_{\rm sp})$, with a typical value of 0.5 seen in numerical simulations.

The high accretion rates of primordial protostars make it likely that the disk will build itself up to a mass that is significant compared to the stellar mass. At this point the disk becomes susceptible to global ($m = 1$ mode) gravitational instabilities (Adams, Ruden, & Shu 1989; Shu *et al.* 1990), which are expected to be efficient at driving inflow to the star, thus regulating the disk mass. Thus TM04 assumed a fixed ratio of disk to stellar mass, $f_d = 1/3$.

Accretion through the disk may also be driven by local instabilities, the effects of which can be approximated by simple Shakura-Sunyaev $\alpha_{\rm ss}$-disk models. Two dimensional simulations of clumpy, self-gravitating disks show self-regulation with $\alpha_{\rm ss} \simeq (\Omega t_{\rm th})^{-1}$ up to a maximum value $\alpha_{\rm ss} \simeq 0.3$ (Gammie 2001), where Ω is the orbital angular velocity, $t_{\rm th} \equiv \Sigma k T_{\rm c,d}/(\sigma T_{\rm eff,d}^4)$ is the thermal timescale, Σ is the surface density, $T_{\rm c,d}$ is the disk's central (midplane) temperature, and $T_{\rm eff,d}$ the effective photospheric temperature at the disk's surface.

Gammie (2001) found that fragmentation occurs when $\Omega t_{\rm th} \lesssim 3$. This condition has the best chance of being satisfied in the outermost parts of the disk that are still optically thick. However, Tan & Blackman (2004, hereafter TB04) considered the gravitational stability of constant $\alpha_{\rm ss} = 0.3$ disks fed at accretion rates given by eq. 2.2 and found that the optically thick parts of the disk remained Toomre stable ($Q > 1$) during all stages of the growth of the protostar. Note that the cooling due to dissociation of H_2 and ionization of H was included in these disk models.

We therefore expect that during the early stages of typical Pop III.1 star formation, the accretion disk will grow in mass and mass surface density to a point at which gravitational instabilities, both global and local, act to mediate accretion to the star. The accretion rates that can be maintained by these mechanisms are larger than the infall rates of eq. 2.2, and so the disk does not fragment.

We note that if fragmentation does occur and leads to formation of relatively low-mass secondary protostars in the disk, then one possible outcome is the migration of these objects in the disk until they eventually merge with the primary protostar. The end result of such a scenario would not be significantly different from the case of no fragmentation. Another possibility is that a secondary fragment grows preferentially from the circumbinary disk leading to the formation of a massive twin binary system (Krumholz & Thompson 2007). If both stars are massive, this star formation scenario would be qualitatively similar to the single star case in terms of the effect of radiative feedback limiting accretion. A massive binary system would mean that the accreting gas needs to lose less angular momentum and binary-excited spiral density waves provide an additional, efficient means to transfer angular momentum, compared to the single star case. For close binaries, new stellar evolution channels would be available involving mass transfer and merger, with possible implications for the production of rapidly rotating pre-supernova progenitors and thus perhaps gamma-ray bursts.

Fragmentation will only be significant for the IMF if it occurs vigorously and leads to a cluster of lower mass stars instead of a massive single or binary system. Clark, Glover, & Klessen (2008) claimed such an outcome from the results of their smooth particle hydrodynamical simulation of the collapse of a primordial minihalo. They allowed dense, gravitationally unstable gas to be replaced by sink particles. They found a cluster of 20 or so protostars formed. As discussed by Clark *et al.* (2008) (see also Glover *et al.*, these proceedings), there are a number of caveats associated with this result. The initial conditions (a sphere of radius 0.17 pc with an uniform particle density of 5×10^5 cm^{-3}, and ratios of rotational and turbulent energy to gravitational of 2% and 10%, respectively) were not derived from ab initio simulations of cosmological structure formation. In particular, cosmologically-formed minihalos evolve towards structures that have very steep density gradients, centered about a single density peak. This is likely to allow the first, central protostar to initiate its formation long before other fluctuations have a chance to develop. The development of a massive central object will create tidal forces in the surrounding gas that will make it more difficult for gravitational instabilities to develop. Furthermore, the surrounding gas is infalling on about a local free fall time, so density perturbations have few local dynamical timescales in which to grow. Another caveat with the Clark *et al.* fragmentation results is the use of a simple tabulated equation of state, in which gas can respond instantaneously to impulses that induce cooling. This, and the form of the equation of state used, lead to near isothermal conditions in the fragmenting region.

4. Magnetic Fields and Hydromagnetic Outflows

TB04 considered the growth of magnetic fields in the accretion disk of Pop III.1 protostars. They estimated minimum seed field strengths $\sim 10^{-16} G$. Xu *et al.* (2008) have recently reported field strengths of up to $10^{-9} G$ generated by the Biermann battery mechanism in their simulations of minihalo formation. Such seed fields are expected to be amplified by turbulence in the disk, attaining equipartition strengths by the time the protostar has a mass of a few solar masses or so. If the turbulence generates large scale helicity, as in the model of Blackman & Field (2002), then this can lead to the creation of dynamically-strong fields that are ordered on scales large compared to the disk. Such fields, coupled to the rotating accretion disk, are expected to drive hydromagnetic outflows, such as disk winds (Blandford & Payne 1982).

TB04 then considered the effect of such outflows on the accretion of gas from the minihalo, following the analysis of Matzner & McKee (2000). The force distribution of centrifugally-launched hydromagnetic outflows is collimated along the rotation axes, but includes a significant wider-angled component. Using the sector approximation, TB04 found the angle from the rotation/outflow axis at which the outflow had enough force to eject the infalling minihalo gas. This angle increased as the protostellar evolution progressed, especially as the star contracted to the main sequence, leading to a deeper potential near the stellar surface and thus larger wind velocities. The star formation efficiency due to protostellar outflow winds remains near unity until $m_* \simeq 100\, M_\odot$, and then gradually decreases to values of 0.3 to 0.7 by the time $m_* \simeq 300\, M_\odot$, depending on the equatorial flattening of surrounding gas distribution. Comparing these efficiencies to those from ionizing feedback (§5), we conclude that the latter is more important at determining the Pop III.1 IMF (see also Tan & McKee 2008).

5. How Accretion and Feedback Set the IMF

MT08 modeled the interaction of ionizing feedback on the accretion flow to a Pop III.1 protostar. In the absence of WIMP annihilation heating, the protostar contracts to the main sequence by the time $m_* \simeq 100\, M_\odot$, and from there continues to accrete to higher masses. At the same time, the ionizing luminosity increases, leading to ionization of the infalling envelope above and below the plane of the accretion disk. Once the H II region has expanded beyond the gravitational escape radius for ionized gas from the protostar, pressure forces begin to act to reverse the infall. In the fiducial case, by the stage when $m_* \simeq 100\,M_\odot$ we expect infall to have been stopped from most directions in the minihalo. Only those regions shadowed from direct ionizing flux from the protostar by the accretion disk are expected to remain neutral and be able to accrete.

In these circumstances the protostar starts to drive an ionized wind from its disk (Hollenbach *et al.* 1994). Ionization from the protostar creates an ionized atmosphere above the neutral accretion disk, which then scatters some ionizing photons down on to the shielded region of the outer disk, beyond r_g. An ionized outflow is driven from these regions at a rate

$$\dot{m}_{\rm evap} \simeq 4.1 \times 10^{-5} S_{49}^{1/2} T_{i,4}^{0.4} m_{*d,\,2}^{1/2} \quad M_\odot\ {\rm yr}^{-1}, \tag{5.1}$$

where S_{49} is the H-ionizing photon luminosity in units of 10^{49} photons s^{-1} and $Ti_{,4}$ is the ionized gas temperature in units of 10^4 K.

MT08 used the condition $\dot{m}_{\rm evap} > \dot{m}_*$ for determining the final mass of the protostar. From numerical models they found it is about $140\,M_\odot$ in the fiducial case they considered, and Table 1 summarizes other cases. MT08 also made an analytic estimate, assuming the H-ionizing photon luminosity is mostly due to the main sequence luminosity of the star:

$$S \simeq 7.9 \times 10^{49}\ \phi_S m_{*,\,2}^{1.5} \qquad {\rm ph\ s}^{-1}, \tag{5.2}$$

which for $\phi_S = 1$ is a fit to Schaerer's (2002) results, accurate to within about 5% for $60\,M_\odot \lesssim m_* \lesssim 300\,M_\odot$. Then the photoevaporation rate becomes

$$\dot{m}_{\rm evap} = 1.70 \times 10^{-4} \phi_S^{1/2} (1+f_d)^{1/2} \left(\frac{T_{i,4}}{2.5}\right)^{0.4} m_{*,\,2}^{5/4}\ M_\odot\ {\rm yr}^{-1}. \tag{5.3}$$

The accretion rate onto the star-disk system is given by equation (2.2). Equating this with equation (5.3), we find that the resulting maximum stellar mass is

$${\rm Max}\ m_{*f,2} = 6.3\ \frac{\epsilon_{*d}^{28/47} \bar{\epsilon}_{*d}^{-12/47} K'^{60/47}}{\phi_S^{14/47} (1+f_d)^{26/47}} \left(\frac{2.5}{T_{i,4}}\right)^{0.24} \rightarrow 1.45, \tag{5.4}$$

where the $\rightarrow$ assumes fiducial values $\epsilon_{*d} = 0.2$, $\bar{\epsilon}_{*d} = 0.25$, $K' = 1$, $\phi_S = 1$, $f_d = 1/3$, and $T_{i,4} = 2.5$ (see MT08 for details; note also here in eq. 5.4 we have corrected a sign error in the index for ϕ_S). This analytic estimate therefore also suggests that for the fiducial case ($K' = 1$) the mass of a Pop III.1 star should be $\simeq 140\,M_\odot$.

The uncertainties in these mass estimates include: (1) the assumption that the gas distribution far from the star is approximately spherical — in reality it is likely to be flattened towards the equatorial plane, thus increasing the fraction of gas that is shadowed by the disk and raising the final protostellar mass; (2) uncertainties in the disk photoevaporation mass loss rate due to corrections to the Hollenbach *et al.* (1994) rate from the flow starting inside r_g and from radiation pressure corrections; (3) uncertainties in the H II region breakout mass due to hydrodynamic instabilities and 3D geometry effects; (4) uncertainties in the accretion rate at late times, where self-similarity may break down (Bromm & Loeb 2004); (5) the simplified condition, $\dot{m}_{\rm evap} > \dot{m}_{*d}$, used to mark the end of accretion; (6) the possible effect of protostellar outflows (discussed above); (7) the neglect of WIMP annihilation heating (discussed above) and (8) the effect of rotation on protostellar models, which will lead to cooler equatorial surface temperatures and thus a reduced ionizing flux in the direction of the disk.

Table 1. Mass Scales of Population III.1 Protostellar Feedback

K'	$f_{\rm Kep}$	$T_{i,4}$	$m_{*,\rm pb}$ $(M_\odot)^1$	$m_{*,\rm eb}$ $(M_\odot)^2$	$m_{*,\rm evap}$ $(M_\odot)^3$
1	0.5	2.5	45.3	50.4	137[4]
1	0.75	2.5	37	41	137
1	0.25	2.5	68	81	143
1	0.125	2.5	106	170	173
1	0.0626	2.5	182	330[5]	256
1	0.5	5.0	35	38	120
1	0.25	5.0	53.0	61	125
0.5	0.5	2.5	23.0	24.5	57
2.0	0.5	2.5	85	87	321

Notes:
[1] Mass scale of HII region polar breakout.
[2] Mass scale of HII region near-equatorial breakout.
[3] Mass scale of disk photoevaporation limited accretion.
[4] Fiducial model.
[5] This mass is greater than $m_{*,\rm evap}$ in this case because it is calculated without allowing for a reduction in $\dot{m}_*$ during the evolution due to polar HII region breakout (see MT08).

Here we discuss briefly the last of these effects. Using the results of Ekström *et al.* (2008) and Georgi *et al.* (these proceedings), we estimate that for a zero age main sequence protostar with $\Omega/\Omega_{\rm crit} = 0.99$ (i.e. rotating very close to break-up), at an angle 80° from the pole (i.e. the direction relevant for the accretion disks modeled by MT08) the surface temperature is reduced by a factor of 0.7. For $m_* = 140\,M_\odot$ this would cause $T_{{\rm eff},*}$ to be reduced from 1.0×10^5 K to 7×10^4 K causing a reduction in the ionizing flux (and thus also ϕ_S) by a factor of about 3. From eq. 5.4 we see that the mass of Pop III.1 star formation would be increased by about a factor of 1.4, to $200\,M_\odot$ in the fiducial case.

6. Evolution of the Pop III.1 IMF

As the universe evolves and forms more and more structure, regions of Pop III.1 star formation will become ever rarer. Indeed, because the effects of radiation from previous stellar generations can propagate relatively freely compared to the spreading and mixing of their metals in supernovae, most metal-free star formation may be via Pop III.2 (Greif & Bromm 2006). Nevertheless, understanding Pop III.1 star formation is necessary as it establishes the initial conditions of what follows.

O'Shea & Norman (2007) 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 find 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 $z = 20$. If Hunter's (1977) solution applies, the mass accretion rates to the protostar will be higher by a factor of 3.7 by the time $m_{*d} = 100\,M_\odot$. These accretion rates then correspond to K'=0.37 ($z = 30$) to 4.3 ($z = 20$). A naive application of eq. 5.4 would imply a range of masses of $40\,M_\odot$ to $900\,M_\odot$. This suggests that the very first Pop III.1 stars were relatively low-mass massive stars, e.g. below the mass required for pair instability supernovae (140–260 $M_\odot$ in the models of Heger & Woosley 2002). Such stars would have had relatively little influence on their cosmological surroundings, thus allowing Pop III.1 star formation to continue to lower redshifts. It is not yet clear from simulations when Pop III.1 star formation was finally replaced by other types, since this depends on the early IMFs of Pop III.1, III.2 and II stars. This transition presumably occurred before reionization was complete.

Acknowledgements

We thank the organizers of IAU255 for a very stimulating meeting. The research of JCT is supported by NSF CAREER grant AST-0645412.

References

Abel, T., Bryan, G. L., & Norman, M. L. 2002, *Science*, 295, 93
Adams, F. C., Ruden, S. P, & Shu, F. H. 1989, *ApJ*, 347, 959
Beers, T. C. & Christlieb, N. 2005, *ARA&A*, 43, 531
Blackman, E. G. & Field, G. B. 2002, Phys. Rev. Lett., 89, 265007
Blandford R. D. & Payne D. G. 1982, MNRAS, 199, 883
Bromm, V., Coppi, P. S., & Larson, R. B. 2002, *ApJ*, 564, 23
Bromm, V. & Loeb, A. 2002, *ApJ*, 575, 111–116
Bromm, V. & Loeb, A. 2004, *New Astron.*, 9, 353
Clark, P. C., Glover, S. C. O., & Klessen, R. S. 2008, *ApJ*, 672, 757
Ekström, S., Meynet, G., Chiappini, C., Hirschi, R., & Maeder, A. 2008, A&A, in press (arXiv:0807.0573)
Freese, K., Bodelheimer, P., Spolyar, D., & Gondolo, P. 2008, arXiv: 0806.0617
Gammie, C. F. 2001, *ApJ*, 553, 174
Greif T. H. & Bromm, V. 2006, *MNRAS*, 373, 128
Heger, A. & Woosley, S. E. 2002, *ApJ*, 567, 532
Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. 1994, *ApJ*, 428, 654
Hunter, C. 1977, *ApJ*, 218, 834
Kashlinsky, A. Arendt, R., Gardner, J. P. *et al.* 2004, *ApJ*, 608, 1
Krumholz, M. R. & Thompson, T. A. 2007, *ApJ*, 661, 1034
Matzner, C. D. & McKee, C. F. 2000, *ApJ*, 545, 364
McKee, C. F. & Tan, J. C. 2008, *ApJ*, 681, 771 (MT08)
Morales, M. F. & Hewitt, J. 2004, *ApJ*, 615, 7
Natarajan, A., Tan, J. C., & O'Shea, B. W. 2008, *ApJ*, submitted (arXiv:0807.3769)
Norman, M. L., O'Shea, B. W., & Paschos, P. 2004, *ApJ*, 601, L115
Omukai, K. & Nishi, R. 1998, *ApJ*, 508, 141
O'Shea, B. W. & Norman, M. L. 2007, *ApJ*, 654, 66
Page, L., Hinshaw, G., Komatsu, E. *et al.* 2007, *ApJS*, 170, 335
Ripamonti, E., Haardt, F., Ferrara, A., & Colpi, M. *MNRAS*, 334, 401
Santos, M. R., Bromm, V., & Kamionkowski, M. 2002, *MNRAS*, 336, 1082
Schaerer, D. 2002, *A&A*, 382, 28
Schaye, J., Aguirre, A., Kim, T-S. *et al.* 2003, *ApJ*, 596, 768
Shu, F. H. 1977, *ApJ*, 214, 488
Shu, F. H., Tremaine, S., Adams, F. C., & Ruden, S. P. 1990, *ApJ*, 358, 495
Spolyar, D., Freese, K., & Gondolo, P., 2008, Physical Review Letters, 100, 051101
Tan, J. C. & Blackman, E. G. 2004, *ApJ*, 603, 401 (TB04)
Tan, J. C. & McKee, C. F. 2004, *ApJ*, 603, 383 (TM04)
Tan, J. C. & McKee, C. F. 2008, First Stars III, eds. O'Shea *et al.*, AIP Conf. Proc., 990, p47
Tegmark, M., Silk, J., Rees, M.J., Blanchard, A., Abel, T., & Palla, F. 1997, *ApJ*, 474, 1
Thompson, R. I., Eisenstein, D., Fan, X. *et al.* 2007, *ApJ*, 657, 669
Xu, H., O'Shea, B. W., Collins, D. C., *et al.* 2008, *ApJ*, submitted (arXiv:0807.2647)
Weinmann, S. M. & Lilly, S. J. 2005, *ApJ*, 624, 526