On the Minimum Metallicity and Mass of the Population II Stars

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ABSTRACT

Within collapsing protogalaxies, thermal instability leads to the formation of a population of cool fragments which are confined by the pressure of a residual hot background medium. The critical mass required for the cold clouds to become gravitationally unstable and to form stars is determined by both their internal temperature and external pressure. We perform a systematic study of the cooling properties of low-metallicity clouds, and we determine, for appropriate ranges of external pressure and metallicity, the minimum temperature clouds can attain prior to the formation of nearby massive stars. The intense UV radiation of massive stars would photoionize the clouds and quench star formation. We also determine the minimum metallicity these clouds must attain in order to form presently observable Population II stars. Based on our conclusion that low-mass stars cannot be formed efficiently in a metal deficient environment, we argue that brown dwarfs are unlikely to be the main contributors to mass in the Galactic halo.

1. Introduction

During the collapse of a protogalactic cloud (PGC), density inhomogeneities and velocity variations lead to shocks which heat the gas to a temperature $T_{\text{hot}} \sim T_{\text{vir}}$, where $T_{\text{vir}}$ is the virial temperature of the galactic halo (Binney 1977; Rees & Ostriker 1977; White & Rees 1978). In order for a PGC to collapse, its cooling time scale, $\tau_c$, must be shorter than the dynamical time scale, $\tau_d$, on which it can contract. For PGC’s with masses comparable to the Galaxy, this condition is satisfied when their characteristic length scale $D < 100 \text{ kpc}$ (Blumenthal et al. 1984).

Subsequent fragmentation of the PGC requires the growth of density inhomogeneities on a time scale, $\tau_g < \tau_d$. If the PGC is cold, gravitational instability causes perturbations with initial amplitude $\delta_0$ to become nonlinear when the system collapses by a factor $\sim \delta_0^{2/3}$ (Hunter 1962). This fragmentation process must proceed on scales down to individual stars as a PGC contracts from an initial size $D = 100 \text{ kpc}$ to the present size (a few kpc) of typical galaxies. For such a small ($\sim 10$) collapse factor, the amplitude of the perturbations must be a few percent for gravitational instability to trigger fragmentation of the PGC.
Large amplitude perturbations would be expected if bona fide normal galaxies are formed as merger products of seed dwarf galaxies with a size $\sim$ a few kpc and a mass $\sim 10^{6-7} M_\odot$ (Blumenthal et al. 1984). Residual gas within these building blocks is expected to virialize prior to the merger events such that $\delta_0$ on the protostellar cloud scale ($\sim 1$ pc) is likely to be small. Gravitational instability alone would not be adequate to induce the fragmentation of PGCs into protostellar objects. However, in the limit that $\tau_c < \tau_d$, thermal instability can lead to the rapid growth of perturbations from infinitesimal $\delta_0$ to nonlinear amplitudes (Field 1965).

For $T_{\text{hot}} \gtrsim 10^5$ K, the dominant cooling mechanisms are bremsstrahlung, HeII line cooling, and H recombination cooling, and $\tau_c$ increases with temperature. In this case, any small temperature difference between the cooler perturbed regions and the background is amplified. Across the boundary of the perturbation, differential cooling leads to a pressure gradient which induces gas flow from the hot background towards the cooler perturbed regions, enhancing the local densities and leading to a runaway cooling process. When the cooling gas reaches a temperature of $T \sim 16000$ K (see below), pressure equilibrium is re-established on all scales, resulting in a two-phase medium with density contrast inversely proportional to the temperature ratio. The residual halo gas (RHG) in the background remains at $T \sim T_{\text{hot}}$ with a density such that its thermal energy is lost on a time scale $\sim \tau_d$. Energy is lost from the RHG through both radiative cooling and thermal conduction between the RHG and the cold clouds (McKee & Cowie 1977). At a distance of $\sim 10$ kpc from the center of a Milky Way sized PGC, the energy balance implies $nT \sim 10^{3-4}$ (Lin & Murray 1997).

In the cooler clouds ($T = 10000$K – 50000K), the dominant cooling mechanism is line emission cooling from a trace amount of HI collisionally excited by free electrons. This process causes a virtually instantaneous cooling to $T \lesssim 16000$K (with $\tau_c \sim 10^4$ yrs for $nT \sim 10^4$), below which the gas starts to recombine and a non-equilibrium treatment of the residual amount of free electrons becomes necessary. The equilibrium cooling function cuts off sharply at lower temperatures because the amount of free electrons is depleted rapidly, causing the cooling to pause at $T \sim 10^4$ K. In reality, however, the cooling time scale is shorter than the H recombination time scale, resulting in a residual fraction of free electrons that can excite HI (and metals, if present) and cause further line cooling. These electrons are also crucial for the formation of molecular hydrogen through the H$^-$ - channel (e.g. Murray & Lin 1992). In metal poor clouds, H$_2$ cooling becomes dominant at $T \approx 6000$K reducing the temperature to $\sim 10^2$K. When metals are present, OI, CI, CO, and grains provide additional cooling. In §2, we perform a detailed study of the cooling of pressure confined clouds as well as clouds with constant densities.

The RHG also exerts a drag on the motion of the clouds as they are accelerated by the gravity of the Galactic halo. The terminal speed of clouds with size $L$ is $V_t \sim (f_n L/D)^{1/2} V_k$ where $f_n$ is the density ratio of the clouds to the RHG, and $V_k$ and $D$ are the velocity dispersion and size of the halo, respectively. The motion of the clouds through the RHG also leads to mass loss due to the Kelvin-Helmholtz instability (Murray et al. 1993), whose growth time scale ($\tau_{KH}$) is a few times $L/V_t$. Because $\tau_{KH}$ increases with $\lambda$, the KH instability leads to fragmentation. The break
down of the clouds increases their collective area filling factor and collision frequency. A balance between disruption and coagulation establishes an equilibrium size distribution (Yorke, Lin & Murray, 1997).

A lower limit to the size distribution of the clouds is set by their evaporation by the hot RHG. In the high mass limit, the self-gravity of the clouds increases the central density and suppresses the Kelvin-Helmholtz instability. But at a critical mass \( M_c \sim T^2/(nT)^{1/2}M_\odot \), thermal pressure can no longer support the weight of the envelope (Bonnor 1956), and the clouds undergo inside-out collapse (Shu 1977). During the collapse, although the Jeans mass decreases with density, it is larger than the mass contained inside any radius. The collapse is stable and does not lead to fragmentation without any further unstable cooling. Thus, contrary to the opacity-limited fragmentation scenario (Hoyle 1953; Low & Lynden-Bell 1976), \( M_c \) represents the minimum mass for isothermal collapsing clouds (Tsai, in preparation).

In a metal-free environment, \( T \sim 10^2 \) K and \( M_c \sim 10^2 - 10^3M_\odot \). Thus, stars formed in a metal-poor environment are massive and short-lived, consistent with their rarity today. Although lower \( T \) and \( M_c \) may be attained in metal enriched clouds, low-mass star formation is regulated by the emergence of massive stars which are copious sources of UV radiation. Photoionization raises \( T \) to above \( 10^4 \) K and \( M_c \sim 10^7M_\odot \). Small (a few \( M_\odot \)) heated clouds are stable and star formation is quenched. Formation of low mass stars is possible provided the clouds can cool to sufficiently low temperature prior to the onset of nearby UV source. In §3, we determine the timescale \( (\tau_{10}) \) for clouds to cool from \( 10^2 \) to 10 K and compare it with the dynamical timescale for relatively massive \( (> 20M_\odot) \) cool (\( 10^2 \) K) clouds to collapse and form upper main sequence stars. We also evaluate the minimum value of \( M_c \) as a function of \( nT \) and \([Fe/H]\). Finally in §4, we discuss the implication of our results for the formation of Population II stars in globular clusters.

2. Cooling of low-metallicity clouds

We are interested in following a gaseous region as it cools and contracts due to the pressure of a surrounding hot, confining gas. For temperatures in the range \( \log T \leq 4.2 \) helium is for all practical purposes fully recombined and does not contribute to the density of free electrons. To calculate the time-dependent, non-equilibrium fractions of electrons and H\(_2\) in the cooling gas we integrate the rate equations for the following network of reactions:

\[
\begin{align*}
H^+ + e^- &\rightarrow H + \gamma \\
H + e^- &\rightarrow H^+ + 2e^-
\end{align*}
\]

\[H + e^- \rightarrow H^- + \gamma
\]

\[H + H^- \rightarrow H_2 + e^-
\]

\[H^- + e^- \rightarrow H + 2e^-
\]


\[ \begin{align*}
\text{H}^- + \text{H}^+ & \rightarrow 2\text{H} \\
\text{H}_2 + \text{H}^+ & \rightarrow \text{H}_2^+ + \text{H} \\
\text{H}_2 + e^- & \rightarrow 2\text{H} + e^-
\end{align*} \]

These are the reactions included in the "minimal model" suggested by Abel et. al. (1996), from which we have taken the expressions for the reaction rates as a function of temperature. This model agrees to within a few percent with a more elaborate model featuring 19 reactions. For the cooling resulting from excitation of the rotational and vibrational states of \( \text{H}_2 \) by \( \text{H}^- - \text{H}_2 \) collisions we adopt the expression given in Tegmark et. al. (1996).

We have included the solutions of the rate equations from the above network and the resulting \( \text{H}_2 \) cooling into a driver code for the photoionization code CLOUDY 90 (Ferland 1996). CLOUDY is used to calculate the HI line cooling as well as cooling from line excitation of metals, as a function of density, temperature, and the non-equilibrium electron density. To follow the time-dependent cooling of the gas we also need to know the evolution of the gas density. Throughout this paper we will describe the gas density by the parameter \( n \), the total number density (in \( \text{cm}^{-3} \)) of hydrogen atoms in a gas with hydrogen and helium mass fractions \( X=0.76 \) and \( Y=0.24 \), respectively. The units of the quantity \( nT \), which can be viewed as a measure of the pressure of a hot, confining medium, is \( \text{K cm}^{-3} \). Two limiting cases will be considered here: 1) \( nT = \text{constant} \) (isobaric) and 2) \( n = \text{constant} \) (isochoric). The first case mimics the compression of a cooling gas cloud by a surrounding, confining medium and applies to regions cooling coherently on length scales small enough for the sound crossing time to be shorter than the cooling time scale. For larger regions (of the same density), the gas cools faster than it can adjust to hydrostatic equilibrium, and is better described by the isochoric cooling model.

The calculations are started at \( \log T = 4.2 \) with the equilibrium value of the hydrogen ionization fraction \( x = 0.54 \) and a negligible fraction of molecular hydrogen. The initial hydrogen number density \( n_0 \) and the metallicity [Fe/H] of the gas are treated as free parameters, and we will examine the properties of the cooling models for \( (nT)_0 \) ranging from \( 10^3 \) to \( 10^5 \) and [Fe/H] from -2 to \( -\infty \). Only C and O turn out to be important coolants, and we assume [C/Fe]=0 and [O/Fe]=0.5, corresponding to the observed enrichment pattern in low-metallicity regions (eg. Wheeler, Sneden & Truran 1989). Dust grains are assumed to be absent. They are likely to play a negligible role in such low-metallicity systems, and it is not possible to model the dust formation process within these cooling clouds in any reliable way.

For illustrative purposes we plot in Figure 1 the value of \( dT/dt \) as a function of \( T \) for [Fe/H]= -3.5, -3, and -2.5 for the isobaric and isochoric models with \( (nT)_0 = 10^4 \). The contribution from \( \text{H}_2 \) is plotted separately. It is seen that for \( [\text{Fe/H}] \lesssim -2 \), \( \text{H}_2 \) is the dominant coolant in the entire temperature interval \( \log T \approx 2.4 - 3.8 \). The most important metal contributor in this interval is OI. The \( \text{H}_2 \) cooling rate cuts off steeply for \( T \lesssim 10^2 \text{K} \), which is the lowest temperature to which a primordial gas can radiatively cool. For \( 10 \text{K} < T < 100 \text{K} \), excitation of the CI (369 \( \mu \text{m} \), 609 \( \mu \text{m} \)) transition (mainly by H-CI collisions) is the dominant cooling mechanism, except for the bump in
the cooling function at around 10^2 K, which is caused by CO. Also note that in the metal deficient limit, cooling below \( T \sim 10^2 \) K is thermally stable since \( T/(dT/dt) \) decreases with \( T \). But for \([\text{Fe}/\text{H}] = -2\), \( dT/dt \propto T \) and the cooling is marginally thermally unstable.

In Figure 2, the evolution of \( T \) for \([\text{Fe}/\text{H}] = -4\), -3, and -2 is shown for the isobaric model with \( nT = 10^4 \). This is an adequate description for the cooling of clouds of sizes

\[
S < S_c \equiv c_s T/(dT/dt), \tag{2}
\]

where \( c_s = \sqrt{kT/\mu m_H} \) is the sound speed in the cloud. As expected, the cooling of a metal free cloud is stalled at \( \sim 10^2 \) K (for the time interval considered, the \([\text{Fe}/\text{H}] = -4\) model is practically identical to a zero-metallicity model). Although it is possible to cool the gas to 10 K for \([\text{Fe}/\text{H}] = -3\), it takes more than \( 3 \times 10^7 \) yrs. As we will argue in the following section, long-living stars with masses \( M \lesssim 1M_\odot \) will only be able to form in an environment where \( T \sim 10^2 \) K, whereas short-lived, massive stars can also form in a 10^2 K environment.

### 3. Minimum stellar mass

In §1, we indicated that the mass spectrum of the cool clouds is determined by an equilibrium between fragmentation due to their interaction with RHC and cohesive collisions. These processes lead some clouds to grow. When an isothermal cloud approaches a critical mass \( M_c \), it becomes self-gravitating and undergoes collapse. The critical value is

\[
M_c \approx 27M_\odot f T^2 \mu^{3/2}(nT)^{1/2}, \tag{3}
\]

where the factor \( f \) is equal to unity in the classical Bonnor-Ebert analysis of the stability of isothermal gas spheres. If, however, the cloud is dynamically perturbed with a finite amplitude, collapse is triggered in less massive clouds, and \( f \approx 1 \). Nonlinear perturbations may be induced by collisions between marginally stable clouds. The mean molecular weight, \( \mu \), is around 1.2 in a neutral medium of H and He, and 2.3 if most of the hydrogen is molecular. In practice, we will absorb the uncertainty in \( \mu \) into the factor \( f \). As will be demonstrated, our inferred minimum metallicity for pop II stars is quite insensitive to variations in that factor. It should be noted that as a cloud builds up and approaches the Bonnor-Ebert mass, it also acquires a density gradient. In equation (3), \( n \) denotes the mean gas density within the Bonnor-Ebert radius.

Let us now look, for a moment, at the properties of present star-forming regions within our Galaxy. Stars of a wide range of masses are known to be forming within dense molecular cores embedded in giant molecular clouds. In these regions, the physical conditions are \( T \sim (10 - 20) \) K and the thermal pressure \( nT \sim 3 \times 10^5 \) (Lada 1993). From equation (3) we find that the collapse of long-lived, low mass stars with \( M \lesssim 1M_\odot \) can be triggered in such regions, provided that \( f \approx 0.3 \). Since the magnetic pressure is comparable to \( nT \) in these cores (Myers 1993), similar critical mass for gravitational unstable magnetized clouds is inferred (McKee et al. 1993). For
larger temperatures, it becomes increasingly more difficult (i.e. requiring lower $f$ and hence larger dynamical perturbations) to form stars of a given mass. We thus expect most, if not all, of the low mass stars to be formed within regions of the lowest attainable temperatures, $T = (10 - 15)$ K, while stars of increasingly higher mass can collapse at increasingly higher temperatures. In the model calculations to be presented below, we will assume that $M_c(T = 10K) < 1M_\odot$ and we will adjust the ratio $f \mu^{-3/2}$ accordingly, for a range of $nT$.

The characteristic dynamical timescale for a cloud is given by

$$\tau_d \equiv (G\rho)^{-1/2} = 8.3 \times 10^7 \text{ yrs}(T/nT)^{1/2},$$

which is the timescale for a cloud to collapse after it becomes marginally unstable. For the clouds that we are considering, it is of order a few million years. In reality, both radiation feedback and rotation can slow down the collapse (Stahler, Shu, & Taam 1980, Yorke et al. 1995). On the other hand, the high density core of the unstable cloud collapses on a shorter timescale than that given by equation (4).

Nevertheless, we adopt the assumption that upper main sequence stars (with $M > M_{\text{UV}}$) begin to release intense UV radiation after a time $\tau_e = \tau_d$ has elapsed from the epoch $t(M_{\text{UV}})$ at which $M_c$ in the clouds is reduced below $M_{\text{UV}}$. From (3) and (4), we find

$$\tau_e = 3.6 \times 10^7 \text{ yrs} f^{-1/4} M_{\text{UV}}^{1/4} \mu^{3/8} (nT)^{-3/8}. $$

We will use the value $M_{\text{UV}} = 20M_\odot$ in all the calculations below because $\tau_e$ depends only weakly on this characteristic mass of strong UV emitters.

A minimum temperature

$$T_{\text{min}} \equiv T(t(M_c = M_{\text{UV}}) + \tau_e).$$

is attainable in a region before it is re-heated by the UV photons from emerging massive stars. The heating and photoionization of the clouds stabilize them against collapse. The value of $T_{\text{min}}$ is a function of [Fe/H] and $nT$. The corresponding minimum mass of stars that can form is,

$$M_{\text{min}} = M_c(T_{\text{min}}).$$

Figure 3 shows $M_{\text{min}}$ as a function of metallicity for $\log nT = 3, 4$, and 5. For each $nT$, $f$ has been chosen so that $M_c(10K)/M_\odot = 0.8, 0.4$, and 0.2, requiring values of $f$ in the interval $[0.001;0.2]$ (for $\mu = 2.3$). Specifically, $f=(0.016,0.008,0.004)$ for $\log nT = 3$, $f=(0.05,0.025,0.013)$ for $\log nT = 4$, and $f=(0.16,0.08,0.04)$ for $\log nT = 5$ respectively. It is evident from Figure 3 that there is a limit in metallicity below which the formation of long-lived stars (with $M < 0.8M_\odot$) is quenched. For $\log nT = 3, 4, 5$, this limit is at $[\text{Fe/H}] \simeq -2, -2.5, \text{ and } -3$, insensitive to the exact choice of $f$.

As an alternative way of presenting these results we plot $T_{\text{min}}$ as a function of metallicity in Figure 4. For clarity we only show the models for which $M_c(10K) = 0.4M_\odot$ here. For low
metallicities, the cooling is too weak to cause any significant temperature reduction below $T(M_{UV})$ during the time $\tau_e$, and the curve is flat. The transitions to $T_{\text{min}} = 10$ K occur sharply around $[\text{Fe/H}] = -2$, -2.5, and -3, the lower limits in metallicity also inferred from Figure 3.

In the above calculations, the isobaric cooling model was used. This assumption is valid provided $M_c$ is less than the mass contained within $S_c$ (equation (2)):

$$M_c < \frac{4}{3} \pi S_c^3 \rho \propto (nT) T^{7/2} / (dT/dt)^3.$$  \hspace{1cm} (8)

Figure 5 shows the mass within $S_c$ and $M_c$ as a function of $T$ for various metallicities in the model with $\log nT = 4, M_c(10 \text{ K}) = 0.8 \text{M}_\odot$. It is clear that the condition (8) is satisfied for all metallicities $[\text{Fe/H}] < -2.5$, so the calculations that determine the minimum metallicity of low-mass stars in Figures 3 and 4 are self-consistent. Similar considerations apply to the other models presented in these figures. For higher metallicities, i.e. on the flat part of the $M_{\text{min}}-[\text{Fe/H}]$ curves, the isobaric approximation gets worse, and the minimum mass becomes uncertain. Also, dust may play an increasingly important role as the heavy element abundance increases.

4. Discussions

Globular clusters contain the oldest and most metal deficient stars in the Galaxy. The results presented here are particularly relevant to the history of star formation in these stellar systems. The presence of low-mass cluster stars today clearly indicate that $M_c << 0.8 \text{M}_\odot$. The expression in (3) indicate that $M_c$ depends on $T$ much more sensitively than $nT$, although the values of both $T_m$ and $M_c(T_m)$ vary more rapidly with $nT$ (see Figure 3). In §1, we presented theoretical arguments to estimate $nT \sim 10^4$. Here we infer the value of $nT$ of proto globular cluster clouds (PCC’s) from the current properties of globular clusters, averaged over their half-mass radius ($r_h$). If both PCCs and the individual clouds are pressure confined, $nT$ is the same for all the entities in the PGC including the RHC.

During globular clusters’ dynamical evolution, their density ($n$) and velocity dispersion at $r_h$ do not change significantly after the epoch of their formation. However, the extrapolation of the physical condition of PCC’s to the stage prior to star formation is highly uncertain. If, after their formation, the stars undergo collapse and virialization from rest, the clouds’ initial radii ($r_i$) would be $\sim 2r_h$. Larger ratios between $r_i$ and $r_h$ would be expected if star formation requires dissipative collisions and coagulation of substellar fragments (Murray & Lin 1996). But $r_i$ is unlikely to be larger than the tidal radii of the PCC’s, which are typically only a few times larger than the present values of $r_h$. Thus, the initial density of PCC’s may be 1-3 orders of magnitude smaller than the average cluster density at $r_h$ today. Based on the present velocity dispersion of the clusters, we infer the initial temperature of the PCC’s to be $\sim 10^4$ K, comparable to that expected if they were photoionized. From these estimates, we infer $nT \sim 10^{2-5}$, and that $nT \propto D^{-3}$ where
$D$ is the cluster's distance to the Galactic center. In accordance with the pressure confinement scenario, both the magnitude and the spatial dependence of PCC’s $nT$ are consistent with those expected for the RHG (Murray & Lin 1992).

From these results, and the cluster metallicities, we can also estimate the cooling time scale and dynamical time scale of the PCC’s. The ratio of these time scales increases from $\sim 10^{-4}$ near the Galactic bulge to $\sim 1$ at $\sim 100$ kpc. In most PCC’s, thermal equilibrium is only possible in the presence of external UV photons with a flux comparable to that required by self regulated star formation in the halo (Lin & Murray 1992). An independent upper limit on $nT$ is inferred for the PCC’s from the requirement that their column density must be less than that would self shielded against the external UV flux (Hellsten, Lin, & Murray 1997). If the value of $nT$ is too small, the PCC’s would be confined by self gravity, in which case the heating and cooling equilibrium is no longer stable (Murray & Lin 1992). Marginal self gravity provides a favorable condition for PCC’s to retain most its gas content against the ram pressure stripping by the RHG (Murray et al. 1993) and for efficient star formation to be triggered by relatively small amplitude perturbations.

Based on the considerations, we estimate $nT \sim 10^{2-5}$. These values of $nT$ are used in Figs 1-4. For this range of $nT$, the results in Figure 3 indicate that the formation of the low-mass stars would be quenched by nearby massive stars unless the GCs were formed from gas that had already been pre-enriched to a metallicity $[\text{Fe/H}] \sim -3$ to -2. At least two general observational results on the metallicity of the globular clusters in the halo of our Galaxy can be easily reconciled with our scenario on the formation of low mass stars. First, the inferred homogeneous metallicity among individual stars within a globular cluster would be expected if the GC is formed out of a well-mixed, pre-enriched PGC rather than being chemically self-enriched (Murray & Lin 1993). Second, the metallicity distribution of globular clusters shows a cut off below $[\text{Fe/H}] \approx -2.5$ (e.g. Ryan & Norris 1991), which is what would be expected if these low-metallicity clusters were formed in an environment with $\log nT \sim 4$. Clusters with $[\text{Fe/H}] < -2.5$ may have formed in this environment at these early epochs, but these cluster would contain mostly massive stars. Mass loss associated with the rapid evolution of massive stars can lead to the disruption of these clusters. In addition, $M_c$ represents the minimum stellar mass. For metal deficient clouds with $[\text{Fe/H}] < -2.5$, $M_c > 1M_\odot$ such that all cluster stars would have evolved off the main sequence phase within the Hubble time.

Our results are also consistent with the rarity of extremely metal-deficient low-mass stars in the Galactic halo. In the outer region of the halo where $nT \sim 10^3$, relatively large values of $[\text{Fe/H}] (> -2)$ are needed for the formation of low $M_c$ stars. The generation of such large amount of heavy elements within one free-fall timescale of the PGC would require the coexistence of $> 10^5$ upper main sequence (earlier than O5) stars. The filling factor of their Stromgren sphere in the PGC would greatly exceed unity such that their UV flux should have quenched star formation well below this level. Based on these considerations, we do not expect the formation of low-mass stars (including brown dwarfs) to be an efficient process in the outer regions of the Galactic halo. Thus, we suggest the stellar or substellar objects are probably not the main contributors to the
mass in the Galactic halo.

On the observational side, a search for stellar objects (MACHO) has led to the identification of several microlensing events toward the direction of the Large Magellanic Clouds (LMC) (Alcock et al. 1996). The characteristic mass of the lensing objects is \(\sim 0.5M_\odot\). If the angular distribution of these objects is uniform, the observed events would not only be sufficient to account for the mass inferred for the Galactic halo, but also contradict our main conclusion that low mass stars cannot form efficiently in the Galactic halo. However, Zhao (1997) suggested these lensing objects in the direction of the LMC may be old stars which were tidally torn from the LMC by the Galaxy. A recent survey provided observational support for the existence of this group of stars between the Galaxy and the LMC (Zaritsky & Lin 1997). The absence of similar stars in other directions suggests that 1) the LMC direction along which lensing objects are found may be special and 2) the density of stellar objects in the Galactic halo remain uncertain.

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REFERENCES

Abel, T., Anninos, P., Zhang, Y. & Norman, M.L., 1997, NewA, accepted [astro-ph/9608040]

Alcock et al., 1996, ApJ, 461, 84.

Binney, J. J. 1977, ApJ, 215, 483

Blumenthal, G. R., Faber, S. M., Primack, J. R., & Rees, M. J. 1984, Nature, 311, 517

Bonnor, W. B. 1956, MNRAS, 116, 356

Ferland, G.J., 1996, University of Kentucky, Department of Astronomy, Internal report

Field, G. B. 1965, ApJ, 142, 531

Hellsten, U., Lin, D.N.C., & Murray, S.D. 1997, in preparation.

Hoyle, F. 1953, ApJ, 118, 513

Hunter, C. 1962, ApJ, 136, 594

Lada, C.J. 1993, in Molecular clouds and star formation, eds. Yuan, C., You, J., World Scientific

Lin, D. N. C., & Murray, S. D. 1992, ApJ, 394, 523

Lin, D.N.C., and Murray, S.D. 1997, in preparation.

Low, C., & Lynden-Bell, D. 1976, MNRAS, 176, 367

McKee, C. F., & Cowie, L. L. 1977, ApJ, 215, 213

McKee, C. F., Zweibel, E.G., Goodman, A.A. & Heiles, C. 1993, in Protostars and Planets III, eds. Levy, H. & Lunine, J.I., University of Arizona Press.

Myers, P.C. 1993, in Molecular clouds and star formation, eds. Yuan, C., You, J., World Scientific

Murray, S. D., & Lin, D. N. C., 1992, ApJ, 400, 265

Murray, S. D., & Lin, D. N. C., 1996, ApJ, submitted

Murray, S. D., White, S. D. M., Blondin, J. M., & Lin, D. N. C. 1993, ApJ, 407, 588

Rees, M. J., & Ostriker, J. P. 1977, MNRAS, 179, 541

Ryan, S.G., and Norris, J.E., 1991, Astron. J., 101,5.

Shu, F. 1977, ApJ, 214, 488
Stahler, S.W., Shu, F.H., & Taam, R.E. 1980, ApJ, 241, 637.

Tegmark, M., Silk, J., Rees, M., Blanchard, A., Abel, T., & Palla, F. 1997, ApJ, 474, 1

Tsai, J., 1997, in preparation.

Wheeler, J. C., Sneden, C., & Truran, J. W. 1989, ARAA, 27, 279

White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341

Yorke, H.W., Lin, D.N.C., & Murray, S.D. 1997, in preparation.

Yorke, H.W., Bodenheimer, P., & Laughlin, G. 1995, ApJ, 443, 119.

Zaritsky, D. & Lin, D.N.C. 1997, AJ, submitted.

Zhao, H. 1997, ApJ, in press.

Figure Captions

Fig. 1.— Cooling rates \(dT/dt\) for isobaric (solid lines) and isochoric (dashed lines) models. \(nT = 10^4 \text{K/cm}^3\) and [Fe/H] = -2.5, -3, and -3.5

Fig. 2.— Temperature as a function of time for isobarically cooling gas with \(nT = 10^4 \text{K/cm}^3\) and [Fe/H] = -2, -3, and -4.

Fig. 3.— Minimum mass of stars that can form within regions with \(\log nT = 3, 4, 5\) as a function of [Fe/H]. For each value of nT, the calculation is performed for the three values of \(M_c(10 \text{K})/M_\odot = 0.8, 0.4, \text{and } 0.2\).

Fig. 4.— Minimum temperature that a star-forming region can acquire prior to reheating by UV radiation from massive stars. Values of nT are indicated on the figure. For the models shown, \(M_C(10 \text{K}) = 0.4 M_\odot\).

Fig. 5.— Mass contained within the radius \(S_c\) of equation (2) as a function of temperature for various metallicities in a model with \(\log nT = 4\) and \(M_c(10 \text{K}) = 0.08M_\odot\) (solid lines). Also shown is \(M_c(T)\) (dashed line).

This preprint was prepared with the AAS \LaTeX\ macros v4.0.
