DARK MATTER DENSITIES DURING THE FORMATION OF THE FIRST STARS AND IN DARK STARS

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ABSTRACT

The first stars in the universe form inside $\sim 10^6 M_\odot$ dark matter (DM) halos whose initial density profiles are laid down by gravitational collapse in hierarchical structure-formation scenarios. During the formation of the first stars in the universe, the baryonic infall compresses the DM further. The resultant DM density is presented here, using an algorithm originally developed by Young to calculate changes to the profile as a result of adiabatic infall in a spherical halo model; the Young prescription takes into account the noncircular motions of halo particles. The density profiles obtained in this way are found to be within a factor of 2 of those obtained using the simple adiabatic contraction prescription of Blumenthal and colleagues. Our results hold regardless of the nature of the DM or its interactions and rely merely on gravity. If the DM consists of weakly interacting massive particles, which are their own antiparticles, their densities are high enough that their annihilation in the first protostars can indeed provide an important heat source and prevent the collapse all the way to fusion. In short, a “Dark Star” phase of stellar evolution, powered by DM annihilation, may indeed describe the first stars in the universe.

Key words: dark matter

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1. INTRODUCTION

The first stars in the universe mark the end of the cosmic dark ages, re-ionize the universe, and provide the enriched gas required for later stellar generations. They may also be important as precursors to black holes that coalesce and power bright early quasars. The first stars are thought to form inside dark matter (DM) halos of mass $10^5$–$10^6 M_\odot$ at redshifts $z = 10$–50 (Yoshida et al. 2003). These halos consist of 85% DM and 15% baryons in the form of metal-free gas made of hydrogen and helium. Theoretical calculations indicate that the baryonic matter cools and collapses via molecular hydrogen cooling (Peebles & Dick 1968; Matsuda et al. 1971; Hollenbach & McKee 1979) into a single small protostar (Omukai & Nishi 1998) at the center of the halo (see, e.g., Ripamonti & Abel 2005; Barkana & Loeb 2001; Bromm & Larson 2004).

Previously, three of us (Spolyar et al. 2008, hereafter Paper I) began a line of research in which we considered the effect of DM particles on the first stars during their formation. Any DM particle which is capable of annihilating with itself is expected to give the correct relic abundance today (Ellis et al. 1988; Gondolo & Silk 1999), in the Sun (Srednicki et al. 1987) and Earth (Freese 1986; Krauss et al. 1986), and in the first stars. We suggested that the very first stellar objects are “Dark Stars,” a new phase of stellar evolution in which the DM—while only supplying $\sim 1\%$ of the mass density inside the objects—provides the power source for the star through DM annihilation. Since we wrote this initial paper, over the past year and a half we have pursued further aspects along this line of research. In this paper, we confirm the presence of the large DM densities required inside the first stars in order for Dark Stars to come into existence.

The canonical example of particle DM is weakly interacting massive particles (WIMPs), which are the favorite DM candidate of many physicists because they automatically provide approximately the right amount of DM, i.e., 24% of the current energy density of the universe. WIMPs are their own antiparticles, and annihilate with themselves in the early universe, leaving behind this relic density. Probably the best example of a WIMP is the lightest supersymmetric particle. In particular, the neutralino, the supersymmetric partner of the W, Z, and Higgs bosons, has the required weak interaction cross-section and mass $\sim$ GeV–TeV to give the correct amount of DM. For a review of Supersymmetry (SUSY) DM, see Jungman et al. (1996). As our canonical values, we used the standard value ($\sigma v$) = $3 \times 10^{-26}$ cm$^3$ s$^{-1}$ for the annihilation cross-section and $m_\chi$ = 100 GeV for the WIMP particle mass, but also considered a broader range of WIMP masses (1 GeV–10 TeV) and cross-sections.

The existence of Dark Stars depends on the fact that the DM densities in these protostars are sufficiently high for the DM annihilation heating to be significant. The first stars are in an advantageous position for high DM densities due to both timing and location: (1) densities scale as $(1 + z)^3$, and the first stars form at high redshifts; (2) they form in the high-density centers

5 This same annihilation process is important wherever the WIMP density is sufficiently high. Such regimes include the early universe, in galactic halos today (Ellis et al. 1988; Gondolo & Silk 1999), in the Sun (Srednicki et al. 1987) and Earth (Freese 1986; Krauss et al. 1986), and in the first stars.

6 The interaction strengths and masses of the neutralino depend on a large number of model parameters. In the minimal supergravity model, experimental and observational bounds restrict $m_\chi$ to 50 GeV–2 TeV, while $(\sigma v)$ lies within an order of magnitude of $3 \times 10^{-26}$ cm$^3$ s$^{-1}$ (except at the low end of the mass range where it could be several orders of magnitude smaller). Nonthermal particles can have annihilation cross-sections that are many orders of magnitude larger (e.g., Moroi & Randall 2000) and would have even more drastic effects. With present state of the field there are many types of DM candidates which could apply (Fargion et al. 2006), including WIMPless DM (Feng & Kumar 2008).
of million solar mass halos of DM. Previously, we obtained estimates for the DM densities inside the first protostars as follows. We started with a variety of initial density profiles laid down by gravitational collapse during hierarchical structure formation (e.g., Navarro, Frenk, and White (NFW) profiles and Burkert profiles). These profiles were then compressed further due to the baryonic quasi-static contraction as the protostar cooled and collapsed. As the baryons come to dominate the potential well in the core, they pull the DM particles inward. Previously we used the simple adiabatic contraction method of Blumenthal et al. (1986, hereafter Blumenthal method, see also Barnes & White 1986; Ryden & Gunn 1987) to estimate the resultant DM density profile. This method is simplistic, in that it assumes all the halo particles move on circular orbits; equivalently only their angular momentum is conserved as the halo is compressed. We found that this method, starting from an NFW profile and compressing further, gave a DM density at the outer edge of the baryonic core

\[ \rho_x \simeq 5 \text{ GeV/cm}^3 (n/cm^3)^{0.81} \] (1)

and scales as \( \rho_y \propto r^{-1.9} \) outside the core. However, a number of authors have compared the Blumenthal method to \( N \)-body simulations of compressed halos in other contexts (galaxies), and warned that the predicted density profiles in those cases were more concentrated than found in their \( N \)-body simulations, especially in the crucial inner part (Barnes 1987; Sellwood 1999; Gnedin et al. 2004). Consequently, there was some concern whether or not the DM densities used in our first paper on Dark Stars were badly overestimated, so that it remained unclear whether or not DM heating in the first protostellar objects is important.

It is the purpose of this paper to show that the DM density in the central core of the protostars does indeed grow high enough for the DM heating to overpower any cooling mechanism, thereby preventing the further collapse of the star and giving rise to a dark star powered by DM annihilation. We follow the approach of Young (1980, hereafter Young method) who presented a general treatment of adiabatic compression of a spherical system. His formulation was originally to model the growth of a black hole in a spherical star cluster, but the method can be applied for any adiabatic change to a spherical potential. It has been used to study halo compression by Wilson (2004) and independently by Sellwood & McGaugh (2005) in galaxies and by Gondolo & Silk (1999) and Merritt (2003) on DM cusps around black holes. The latter authors found that the simplistic Blumenthal method overestimated the central densities in galaxies by factors of 2 or 3, but not by several orders of magnitude, even when radial pressure and disk geometry are taken into account. Here we apply Young’s method, as adapted by Sellwood & McGaugh, to protostellar Pop III objects in order to obtain the DM densities inside their cores.

It is important to point out that Young’s (1980) adiabatic prescription is not at all sensitive to departures from sphericity—Sellwood & McGaugh (2005) showed that, for what concerns adiabatic contraction, even a flat disk could be well approximated as a sphere.

We briefly mention here other previous work on DM annihilation in stars. DM annihilation in the Sun was considered by Krauss et al. (1985); indirect detection due to DM annihilation in the Sun as a possible way to find WIMPs was proposed by Srednicki et al. (1987); indirect detection in the Earth as a possible way to find WIMPs was proposed by Freese (1986) and Krauss et al. (1986); indirect detection due to annihilation at the Galactic Center was proposed by Gondolo & Silk (1999); effects of nonannihilating WIMPs on convection in stars was considered by Bouquet & Salati (1989a). The role of DM annihilation on the evolution of the Sun and other Population I main-sequence stars, including in galactic nuclei leading to black hole formation, was previously studied by Bouquet & Salati (1989b) and Salati & Silk (1989). Here, the notation Population I refers to the most recent generation of stars (including today), Population II to earlier stars, and Population III to the earliest stars (\( z > 10 \) or so). In the last few years, other work on DM annihilation powering stars has also been done in the context of high DM densities near the supermassive black holes in galactic centers, e.g., WIMP burners (Moskalenko & Wai 2007) and more generally Scott et al. (2007) and Bertone & Fairbairn (2008).

In another paper, we considered DM capture as another source to increase DM density in the first stars, which becomes important once their baryon densities are near stellar densities; in particular, we considered the effects of DM annihilation on early zero-metallicity (Population III) stars, once they do have fusion inside their cores (Freese et al. 2008). A very similar work was simultaneously submitted by Iocco (2008). These stars live inside a reservoir of WIMPs; as the WIMPs move through the stars, some of the WIMPs are captured by the stars. The captured DM sinks to the center of the stars, where it adds to the DM annihilation. We found that DM annihilation may dominate over fusion, and the DM power source may exceed the Eddington luminosity and prevent the first stars from growing beyond a limited mass. Even when capture is important, it too is dependent upon adiabatic contraction in order to achieve the high DM densities required.

The DM profiles obtained in this paper are appropriate to any type of collisionless DM, not just WIMPs. This work relies upon the gravitational response of the halo to the baryons alone, and requires only that the DM particles are both collisionless and interact with the baryons only through gravitational forces. We also need to make an assumption about the velocity distribution of the DM particles in the very centers of these small halos, which we take to be isotropic.

The protostellar clouds (unlike galaxies as a whole) are baryon-rich environments. For hydrogen density \( n > 10^4 \text{ cm}^{-3} \), the baryon density exceeds the DM density in the collapsing protostar. We note that the angular momentum of the collapsing baryons is transferred to baryons via gas dynamics rather than being transferred to DM gravitationally. In addition, although in hierarchical structure formation at these redshifts there are significant mergers, simulations of the first star formation have found that in such a scenario reasonably well isolated stars are formed; thus treating the baryons and DM as well isolated in these small star-forming regions is sensible (Yoshida et al. 2003; Abel et al. 2002). In Section 2, we will review the various methods for halo compression. In Section 3, we present our results in the first protostellar objects. We conclude in Section 4.

2. METHODS TO OBTAIN THE DM DENSITY

In this paper, we assume adiabaticity of the protostellar collapse. In other words, since the change of the gravitational potential is not too substantial over a single orbital time scale during the phase we are studying, we may take the adiabatic invariants to be well conserved.

The DM contracts adiabatically if the fractional change in the interior mass is small in one dynamical crossing time. This
time becomes very short in the center as the collapse proceeds, implying that the adiabatic approximation is very good in the center, where you require an accurate calculation of the DM density. The approximation is more questionable at larger radii, because of the longer crossing times, variable tidal fields, etc. Yet previous simulations of the first stars (e.g., Abel et al. 2002) showed that what happens farther out does not affect the baryonic collapse. Equally, the tightly bound DM in the center will not be disturbed by fluctuations in the much lower density DM farther out.

2.1. Initial DM Density Profiles: NFW and Core

With this assumption of adiabaticity, we follow the response of the DM to the collapse of the protostellar object. As our initial conditions for the DM before contraction, we take an overdense region of $10^{5} - 10^{6}\ M_\odot$ with a NFW profile (Navarro et al. 1996) for both DM and gas, where the gas contribution is 15% of that of the DM. The density profile of an NFW halo is

$$\rho(r) = \frac{\rho_0}{x(1 + x)^2},$$

where $x = r/r_s$, $r_s$ is the break radius of the profile, and $\rho_0 \equiv 4\rho(r_s)$ sets the density scale. The critical density of the universe varies with redshift $z$ as

$$\rho_c(z) = \frac{3H^2(z)}{8\pi G}.$$  \hspace{1cm} (3)

The Hubble parameter in a flat universe varies as

$$H^2(z) = H_0^2[\Omega_m(1 + z)^3 + \Omega_\Lambda].$$  \hspace{1cm} (4)

where the current matter density is $\Omega_m \sim 0.25$, and the $\Omega_\Lambda$ term (dark energy) on the right-hand side can be neglected at the redshifts we are considering. We find $H^2(z = 19) \approx 2000H_0^2$, where today's Hubble constant $H_0 = 100\ h\ km\ s^{-1}\ Mpc^{-1}$ with $h \sim 0.5$. For an NFW halo of mass $M_{200} = 7 \times 10^5\ M_\odot$, and taking $3M_{200}/4\pi r^3 = 200\rho_c(z)$,

$$\frac{3M_{200}}{4\pi r^3} = 200\rho_c(z),$$

(5)

gives $r_{200} \sim 123\ pc$. For a value of the concentration parameter $c \equiv r_{200}/r_s = 2$, we have $r_s = 61.5\ pc$.

For comparison, we also use the extreme case of a profile which has a constant-density DM core in the inner region before contraction. Such a core is not physically motivated, and we consider it only to illustrate that our results still hold even in this extreme case. In fact, recent simulations (Diemand et al. 2008) indicate that the profiles are more rather than less steep in the inner core compared to NFW, as $\rho_x \propto r^{-1.2}$, instead of $\rho_x \propto 1/r$. To illustrate the generality of our results, in this paper we consider as our starting points the NFW and (the unphysical) flat-cored profiles.

Given these initial profiles for the DM, we can follow their response to the changing baryonic gravitational potential as the protostellar gas condenses. The gas density profiles during the protostellar collapse we use are taken from simulations of Abel et al. (2002, Figure 2) and Gao et al. (2007). Roughly, the profiles of the hydrogen number density have the functional form $n(r) = \frac{n_{\text{core}}}{1 + r/r_f}$. The profile is flat from the origin out to (almost) $r_g$, where it turns over to $n \sim r^{-2.3}$. The core densities $n_{\text{core}}$ and turnover radii $r_g$ are taken from Abel et al. (2002) and Gao et al. (2007). We note that the hydrogen number density

should be multiplied by $\sim 1.35$ to obtain the total gas density, in order to account for the additional presence of helium in the collapsing protostellar cloud.

Below we will describe the results of adiabatic contraction for the DM that we previously obtained using the Blumenthal method, and then turn to the more accurate Young method to find better DM density profiles in the collapsing protostellar objects.

2.2. Previous Estimates of the DM Density Profile Using the Blumenthal Method

We previously used the Blumenthal method for adiabatic contraction (Blumenthal et al. 1986; Barnes & White 1986; Ryden & Gunn 1987) to obtain estimates of the DM profile as the first protostars condensed. As previously mentioned, this method assumes that DM particles conserve angular momentum as the halo is compressed (other adiabatic invariants set to zero); i.e., all particles are on circular orbits. One can assume that a particle at radius $r_i$ is pulled in to a radius $r_f$. Then one finds that $M_f(r_f) r_f = M_i(r_i) r_i$, where $M(r)$ is the total mass inside radius $r$ and final quantities use the perturbed potential (due to baryonic infall) for their evaluation. Additionally, the assumption is made that dissipationless particle orbits do not cross (since particles are on circular orbits). After contraction, we found the DM density at the outer edge of the baryonic core is roughly given by Equation (1) and scales as $\rho_x \propto r^{-1.9}$ outside the core. Our results are shown in Figure 1.

One can compare our adiabatically contracted NFW profiles obtained via the Blumenthal method with the DM profiles found numerically in Abel et al. (2002) for the first collapsing protostellar clouds (see their Figure 2). While these authors obtained remarkably good density profiles for the collapsing protostellar gas in to very small radii, they found DM density

![Figure 1. Adiabatically contracted DM profiles for the first collapsing protostars using the Blumenthal method for an initial NFW profile (solid black line). Resulting curves correspond to hydrogen densities of $n = 10^{15}$ cm$^{-3}$ (blue dashed lines) and $n = 10^{16}$ cm$^{-3}$ (red dotted lines). For comparison, the black dots show the DM densities obtained in the numerical simulations of Abel et al. (2002; Figure 2A) corresponding to $n = 10^{13}$ cm$^{-3}$. Excellent agreement is seen; the outer profile for all cases scales as $\rho \propto r^{-1.9}$.

(A color version of this figure is available in the online journal.)](image-url)
profiles only up to radii that are several orders of magnitude larger in extent. In their paper they presented two DM profiles (their earliest and latest profiles), for \( n \sim 10^3 \text{ cm}^{-3} \) and \( n \sim 10^{13} \text{ cm}^{-3} \) as far inward as 0.1 pc and 5 \times 10^{-3} \text{ pc}, respectively. The slope of these two curves is the same as ours, \( \rho_x \propto r^{-1.9} \). If one uses this slope and extrapolates inward to smaller radii and to higher densities, then one obtains the same DM densities as with our adiabatic contraction approach, as seen in Figure 1. Although we are encouraged by this agreement, one might still worry about the extrapolation of the DM in toward radii smaller than the ones treated by Abel et al. (2002).

Hence it is the purpose of this paper to improve upon the Blumenthal method approximations used in Paper I and to obtain better estimates of the DM density profiles inside the collapsing baryonic core in the first protostars. We note that \( N \)-body simulations (without assuming adiabaticity) to further confirm the DM profiles obtained in this work after baryonic compression are in progress (M. Zemp 2009, in preparation).

2.3. New Estimate of DM Density Using Young’s Method

As discussed in Section 3.6 of Binney & Tremaine (1987), adiabatic changes conserve all three actions of an orbit. In this paper we do indeed work with the assumption that the growth of the protostellar object is adiabatic. In general, if no further assumptions are made, one needs to consider all three actions, and the problem becomes analytically intractable, though it can still be followed with \( N \)-body simulations. In a spherical system, however, the problem reduces to two conserved actions and becomes tractable: these two actions are the angular momentum and radial action, while the third action is identically zero because the plane of each orbit is an invariant. Thus, adiabatic compression of a spherical halo needs to take account of the conservation of radial action, as well as of angular momentum. Whereas the Blumenthal method makes the further restriction of only circular orbits so that only angular momentum is conserved, Young (1980) described an algorithm to take into account the conservation of both of these adiabatic invariants. The central idea of his method is to require the distribution function to be invariant during adiabatic changes:

\[ f_i(J_r, J_n) = f_o(J_r, J_n), \]

where \( J(E, L) \) is the radial action and \( J_n \equiv L \) is the azimuthal action, or total angular momentum per unit mass. Here, subscripts \( i \) and \( n \) refer to the initial and new halo profiles, computed in the changing potential well due to baryonic infall.

Sellwood & McGaugh (2005) implemented Young’s method for halo compression in galaxies (see also Wilson 2004). In their paper, they describe an iterative procedure for obtaining a DM density profile in response to a baryonic mass inside the halo that condenses. They focused on a growing disk inside a galaxy, and the consequent DM particle compression in the central region of the galaxy. They showed that Young’s prescription was successful (matched numerical results) even for a flat disk; indeed the method is not restricted in practice to spherical systems. In this paper, the code of Sellwood & McGaugh is applied to the problem of the first protostars, with this same iterative procedure following the compression of the DM halo as the protostellar core collapses.

The method works by relating the distribution function of the compressed halo to that of the original halo through the two conserved actions, assuming the compression is adiabatic. It is therefore necessary to compute (1) the radial action from the energy and angular momentum in the compressed potential, and then (2) the energy in the original halo for the same radial action and angular momentum. A numerically efficient procedure is to interpolate from tables of these quantities, and the radial action table for step (1) has to be recomputed at each iteration. Since the first stars are much smaller, relative to the NFW break radius, than the galaxy disks used in the previous application, we increased the sizes of the tables to 200\(^2\) values in order to achieve the desired precision. The final density profile generally converged satisfactorily in a few, typically three or four, iterations.

3. RESULTS

We find the adiabatic contraction of DM densities due to the collapsing gas densities in the inner regions of the first collapsing protostellar clouds. Our results can be seen in Figures 2 and 3 as well as Table 1.

3.1. Initial NFW Profile

We can start from an initial NFW halo profile for both the DM and the baryons, with the baryons comprising 15% of the total mass. Starting from initial NFW halos (dashed line in the figure), Figure 2 plots contracted density profiles using (a) the standard Blumenthal method for adiabatic contraction (dotted lines) and (b) the Young method (solid lines), for a variety of hydrogen densities, \( n = 10^4, 10^5, 10^{13}, \) and \( 10^{16} \text{ cm}^{-3} \) for a total DM halo mass of \( 7 \times 10^5 M_\odot \) and a concentration parameter \( c = 2 \) at \( z = 19 \). The upper panel illustrates the DM density profile and the lower panel illustrates the enclosed DM mass \( M(r) \) as a function of radius. Both profiles are shown in to a radius of \( 10^{-4} \text{ pc} \).

The main result of our paper is that the densities computed in both ways differ by no more than a factor of 2. In some cases the Blumenthal method yields a higher density, while in other cases the Young method yields a higher density; yet the difference never exceeds a factor of 2. One can see that the DM density is not enhanced at small radii for low gas density \( n = 10^4 \text{ cm}^{-3} \); this is because the amount of gas mass at these radii is simply too small. However, once the protostellar cloud gets to \( n = 10^8 \text{ cm}^{-3} \) or higher, the DM density is substantially enhanced due to adiabatic contraction using either method. One might also ask why the Blumenthal formula yields a lower predicted density than Young’s formula at small radii, as the plot shows for the two lower density stars. The answer is that a halo particle on a noncircular orbit spends part of its time at large radii where the interior compressing mass is larger than when it is close to the center. Thus, the mean density can be increased even when little compressing mass is interior to that radius—this can happen only where the star has a diffuse core.

We note that the curves for \( n = 10^{16} \text{ cm}^{-3} \) do not look substantially different from those of \( n = 10^{13} \text{ cm}^{-3} \). This is because at the radius of \( 10^{-4} \text{ pc} \) the two curves are just beginning to diverge. At smaller radii, the higher gas density would lead to substantially higher DM density: i.e., we expect that the DM density for the \( 10^{16} \text{ cm}^{-3} \) curve would be much higher than that for the \( 10^{13} \text{ cm}^{-3} \) curve at a radius of \( 10^{-6} \text{ pc} \), but we do not have the resolution to show this explicitly. In short, starting from an NFW profile, we have confirmed that the DM density in the inner regions of the protostellar cloud is substantially enhanced due to contraction during gas collapse.

3.2. Initial Cored Profile

For comparison, we also use the extreme case of a profile which has an initial constant density DM core in the inner
region before contraction. Such a core is physically unmotivated (in fact it is not self-consistent given the hypothesis of WIMP DM); the results of the previous section, starting from an initial NFW profile, are far more likely to be realistic. In fact, recent simulations (Diemand et al. 2008) indicate that the profiles are more rather than less steep in the inner core compared with NFW, with \( \rho_x \propto r^{-1.2} \) rather than \( \rho_x \propto 1/r \).

The reason that we include the unphysical case of a constant density core in this paper is to illustrate the generality of our results: even in this extreme situation, again we find substantially enhanced DM densities due to contraction during gas collapse. However, for quantitative studies of Dark Stars, the final density profiles obtained starting from an initial NFW profile should be used instead (and may indeed be conservative).

We now stare with a DM core as the initial condition instead of an NFW profile. Figure 3 plots the contracted density profiles obtained with the same two techniques (Blumenthal and Young). We take as our initial core DM density \( \rho_x \sim 3 \times 10^4 \) (with a core radius of 0.2 pc). This value is motivated by the DM density found by Abel et al. (2002, Figure 2A) corresponding to a hydrogen density of \( 10^3 \) cm\(^{-3} \); their numerical results were found only in to a radius \( \sim 0.1 \) pc, and we simply take the value

### Table 1

| Radius (pc) | DM Density w/ Young Method | DM Density w/ Blumenthal Method |
|-------------|---------------------------|---------------------------------|
| 2.42 \times 10^{-4} | 1.17 \times 10^{10} GeV cm\(^{-3} \) | 2.14 \times 10^{10} GeV cm\(^{-3} \) |
| 9.30 \times 10^{-4} | 1.07 \times 10^{9} GeV cm\(^{-3} \) | 1.95 \times 10^{9} GeV cm\(^{-3} \) |
| 1.11 \times 10^{-2} | 1.13 \times 10^{7} GeV cm\(^{-3} \) | 2.07 \times 10^{7} GeV cm\(^{-3} \) |
| 0.108 | 1.75 \times 10^{5} GeV cm\(^{-3} \) | 3.16 \times 10^{5} GeV cm\(^{-3} \) |
| 1.08 | 3.02 \times 10^{3} GeV cm\(^{-3} \) | 5.13 \times 10^{3} GeV cm\(^{-3} \) |

Note. The two methods agree to within a factor of 2.
they found near that radius to be constant inward all the way to the origin. Clearly, this gives an underestimate of the initial DM density in the central region of the DM halo. Even in this case, the DM density is substantially enhanced by the subsequent gas collapse. This initial profile is not meant to be realistic and is presented merely as an extremely conservative illustration of the two techniques for obtaining the DM density profile. In Figure 3, the three curves correspond to hydrogen densities $n = 10^4, 10^8,$ and $10^{13} \text{ cm}^{-3}$. The upper panel illustrates the resultant DM profiles and the lower panel illustrates the enclosed DM mass as a function of radius. Again, the DM density is substantially enhanced due to contraction during gas collapse. We note that, on the smallest scales and highest densities (the $10^{13}$ cored case), the plots look irregular (particularly on logarithmic scales) due to a sparse numerical grid, which has fewer points in the inner region for this cored case.

Our general conclusion is that DM densities are indeed substantially enhanced in the presence of the collapsing baryonic protostellar cloud. Due to the resultant large DM densities, the DM heating becomes substantial and the Dark Star proposed in Paper I does indeed come into existence at this point.

4. DISCUSSION

As the first stars form inside DM halos, the protostellar baryons gravitationally pull the DM farther inward. Regardless of the nature of the DM: simply due to gravity, the density of any type of DM in the inner regions of the collapsing Population III protostars will be enhanced by the baryonic infall. In this paper we computed the changes to the DM density profile in the protostellar cores due to adiabatic increase of gas densities in these cores. We used Young’s method appropriate for spherical halos, which takes into account the conservation of both angular momentum and the radial action. With this method we found DM density profiles after contraction with central densities no more than a factor of 2 different than those obtained previously (Spolyar et al. 2008) via a simple Blumenthal model for adiabatic contraction (which takes into account only circular orbits). The central DM densities in the protostar are substantially enhanced during the gas collapse. Recent simulations (Via Lactea II, Diemand et al. 2008) find initial DM density profiles that are steeper in the inner core compared with NFW, $\rho_x \propto r^{-1.2}$ rather than $\rho_x \propto 1/r$, so
that DM densities we have found via either technique may in fact be underestimates of the actual DM density. Note that the compressed halo densities we obtain when we assume either that halo particles have entirely circular orbits or an isotropic velocity distribution do not differ by much; we do not therefore expect our conclusions to be at all sensitive to any assumption for the distribution of halo particle velocities. N-body simulations (without assuming adiabaticity) to further confirm the DM profiles obtained in this work after baryonic compression are also in progress (M. Zemp 2009, in preparation). We also reiterate that Young’s adiabatic prescription is not at all sensitive to departures from sphericity, as shown for a flat disk by Sellwood & McGaugh (2005).

If the DM consists of DM particles that annihilate among themselves (the prototypical example is neutralino supersymmetric particles), then these high DM densities lead to substantial DM annihilation to the point where DM heating dominates in the stellar core and prevents further collapse. Indeed a Dark Star is created, powered by DM annihilation rather than by fusion.

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