Dark Matter and the First Stars: A New Phase of Stellar Evolution

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A mechanism is identified whereby dark matter (DM) in protostellar halos dramatically alters the current theoretical framework for the formation of the first stars. Heat from neutralino DM annihilation is shown to overwhelm any cooling mechanism, consequently impeding the star formation process and possibly leading to a new stellar phase. A "dark star" may result: a giant ($\gtrsim$1 AU) hydrogen-helium star powered by DM annihilation instead of nuclear fusion. Observational consequences are discussed.

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The first stars in the Universe mark the end of the cosmic dark ages, reionize the Universe, and provide the enriched gas required for later stellar generations. They may seed black holes that coalesce and power bright early quasars. The first stars are thought to form inside halos of dark matter of mass $10^5 M_\odot$–$10^6 M_\odot$ at redshifts $z = 10$–50. These halos arose from the merging of smaller structures, as overdense regions in the Universe assemble hierarchically into ever larger halos. The halos consist of 85% dark matter and 15% baryons in the form of pristine hydrogen and helium (from big bang nucleosynthesis). The baryonic matter cools and collapses via molecular hydrogen cooling [1–3] into a single small protostar [4] at the center of the halo (for reviews see, e.g., [5–7]).

In this Letter we consider the effect of dark matter (DM) particles on the formation process of the first stars. We focus on the most compelling DM candidate, the lightest supersymmetric particle (LSP). Supersymmetry (SUSY) has the capability of addressing many unanswered questions in particle theory as well as providing the underpinnings of a more fundamental theory such as string theory. If SUSY is right, then for every known particle in the Universe, there is an as yet undiscovered partner. The lightest of these, the LSP, would provide the DM in the Universe. The search for SUSY is one of the motivations for building the Large Hadron Collider at CERN, and one may hope that it will be discovered as early as 2008.

The SUSY particles, also known as WIMPs (weakly interacting massive particles), are the favorite DM candidate of many physicists because they automatically provide 24% of the energy density of the Universe. The WIMPs are in thermal equilibrium in the early Universe, and annihilate among themselves to produce the relic density today. In particular, the neutralino, the SUSY partner of the W, Z, and Higgs bosons, has the required weak interaction cross section and ~GeV–TeV mass to give the correct amount of DM. It is this same annihilation process that is the basis of the work we consider here. WIMPs annihilate with one another wherever their density is high enough. Such high densities are achieved in the early Universe, in galactic halos today [8,9], in the Sun [10] and Earth [11,12], and, as we will show, also in the first stars. As our canonical values, we will use the standard value $\langle\sigma v\rangle = 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$ for the annihilation cross section and $m_\chi = 100$ GeV for the SUSY particle mass, but will also consider a broader range of WIMP masses (1 GeV–10 TeV) and cross sections [13]. The effects we find apply equally well to other WIMP candidates, such as sterile neutrinos or Kaluza-Klein particles.

Previous work [15,16] on the effects of DM annihilation on the first stars examined the early phases of their formation (low gas density $n \lesssim 10^4\ \mathrm{cm}^{-3}$). They rightly concluded that 100 GeV neutralinos cannot heat these low density protostars because the annihilation products simply escape out of the object without depositing much energy inside. They consequently focused on lighter particles, such as 1–10 keV sterile neutrinos and 1–100 MeV light DM. In this Letter, we focus instead on typical 1 GeV–10 TeV WIMP masses and find a regime (gas density $>10^{13}\ \mathrm{cm}^{-3}$) where these particles play a crucial role in the evolution of the first stars.

DM density profile.—To study the effects of DM on star formation, we need to know its density profile inside the baryonic core that is collapsing to form the star. While simulations have obtained remarkably good density profiles for the collapsing protostellar gas, they have unfortunately (as yet) been unable to do so for the DM. Thus we use adiabatic contraction [17] to obtain estimates of the DM profile. As our initial conditions, we take an overdense region of $10^5 M_\odot$–$10^6 M_\odot$ with a Navarro-Frenk-White (NFW) profile [18] for both DM and gas, where the gas contribution is 15%. (For comparison, we also use a Burkert profile [19], which has a DM core before contraction.) As the gas collapses, we allow the DM to respond to the changing baryonic gravitational potential (gas density profiles taken from simulations of [20,21]). The final DM density profiles are computed with adiabatic contraction [$M(r)r = \mathrm{const}$], as shown in Fig. 1 for concentration parameter $c = 10$ at $z = 19$ and halo mass $M = 10^6 M_\odot$. Our results do not change much for other choices of these

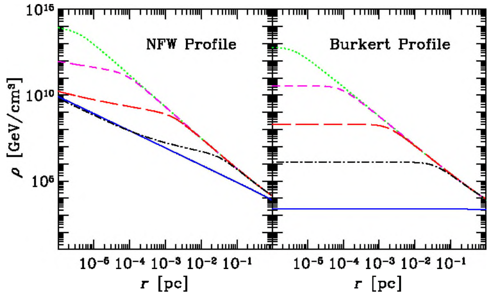

FIG. 1 (color online). Adiabatically contracted DM profiles for (a) an initial NFW profile and (b) an initial Burkert profile, for $M_{\rm vir} = 10^6 M_\odot$, $c_{\rm vir} = 10$, and $z = 19$. The solid (blue) lines show the initial profile. Dot-dashed (black) lines correspond to a baryonic core density $n \sim 10^7$ cm^{-3}, long-dashed (red) lines to 10^{10} cm^{-3}, dashed (magenta) lines to 10^{13} cm^{-3}, and dotted (green) lines to 10^{16} cm^{-3}.

parameters; e.g., even for $c = 1$, the DM density only changes by a factor of 4. After contraction, the DM density at the outer edge of the baryonic core is roughly $\rho_\chi \simeq 5$ GeV/cm$^3 (n/\text{cm}^3)^{0.81}$ and scales as $\rho_\chi \propto r^{-1.9}$ outside the core.

Our adiabatically contracted NFW profiles match the DM profile obtained numerically in [20] (see their Fig. 2). They present their earliest (gas core density $n \sim 10^3$ cm^{-3}) and latest ($n \sim 10^{13}$ cm^{-3}) DM profiles, as far inward as 5×10^{-3} pc and 0.1 pc. The slope of these two curves is the same as ours. If one extrapolates them inward to smaller radii, one obtains the same DM densities as with our adiabatic contraction approach. We are encouraged by this agreement.

As a caveat, we note that the approach of adiabatic contraction must be used with caution. It formally requires the orbital particle time to be short compared to the collapse time, though in practice the method works well beyond this limit (see, e.g., [22]). We are also concerned about the requirement of spherical symmetry, when, in fact, there are filaments, clumps, and mergers, so that dynamical friction or violent relaxation may take place. The gas may form bars that could sweep out DM, though the rotation time scale for bars may be too long for them to be important. We encourage simulators to improve the DM resolution in first stars to confirm our results. The closest previous work is that of Merritt [23], who used initial profiles $\rho \propto r^{-\gamma}$ with $\gamma = [0, 2]$ around a central black hole and found final profiles $\rho \propto r^{-\gamma'}$ with $\gamma' = [2.25, 2.5]$ (i.e., even steeper than ours). We caution the reader that our heating estimates below rely upon DM densities obtained with these assumptions.

DM heating.—WIMP annihilation in the first stars produces energy at a rate per unit volume

$$\begin{aligned} Q_{\rm ann} &= \langle \sigma v \rangle \rho_\chi^2 / m_\chi \\ &\simeq 1.2 \times 10^{-29}\ \text{erg/cm}^3/\text{s}[\langle \sigma v \rangle / (3 \times 10^{-26}\ \text{cm}^3/\text{s})] \\ &\quad \times (n/\text{cm}^{-3})^{1.62} [m_\chi / (100\ \text{GeV})]^{-1}. \end{aligned}$$

In the early stages of star formation, when the gas density is low, most of this energy is radiated away. However, as the gas collapses and its density increases, a substantial fraction f_Q of the annihilation energy is deposited into the gas, heating it up at a rate $f_Q Q_{\rm ann}$ per unit volume.

Here we estimate f_Q. This quantity scales linearly with the gas density and depends on the relative number of the various annihilation products and their energy spectrum. The latter are heavily dependent on the WIMP model. From our experience with neutralino DM, we assume the following typical values: $\sim 1/3$ of the energy goes into neutrinos, $\sim 1/3$ into photons, and $\sim 1/3$ into stable charged particles like electrons and positrons. Unstable particles like π^0, $\pi^\pm$, and $\mu^\pm$ decay into photons, neutrinos, and electrons before exiting the cloud. The energy spectrum of photons and electrons depends to some extent on the exact annihilation channels. For our purpose, we consider typical spectral shapes produced in PYTHIA simulations of 500 GeV neutralino annihilation [24,25]. Other spectral shapes will change the precise values of our results but not the overall effect.

Neutrinos escape without depositing an appreciable amount of energy. Electrons above a critical energy $E_c \approx 280$ MeV in hydrogen initiate an electromagnetic (EM) cascade, as do photons $\gtrsim$100 MeV. Lower energy electrons lose energy predominantly by ionization, and lower energy photons Compton scatter off electrons in the gas. We approximate the ionization energy loss of electrons with 4.41 MeV/E (g/cm^2)$^{-1}$. For EM cascades, we assume a Γ distribution for the mean longitudinal profile: the fraction of energy lost in traversing a thickness X of gas equals $\gamma(a, bX/X_0)/\Gamma(a)$, where $\gamma(x, y)$ is the incomplete gamma function, $X_0 = 63$ g/cm^2 is the radiation length in hydrogen, $a = 1 + b[\ln(E/E_c) - 0.5]$, and $b = 0.5$ [26]. We estimate the core thickness as $X = 1.2 m_p n r_0$. Here m_p is the proton mass, r_0 is the core radius, and the factor of 1.2 is appropriate for a uniform sphere. We model the fraction of energy loss of photons by converting each photon to an electron of the same energy after one photon attenuation length. The latter is computed from formulas in [27], interpolated to produce the hydrogen curve in [26], Fig. 27.16.

Annihilation of DM outside the core can also contribute to heating inside the core. With a profile $r^{-2.3}$, we find a 25% enhancement in core heating due to the external region. We neglect this enhancement.

Results.—To compare with DM heating, we include all relevant cooling mechanisms. The dominant mechanism is H_2 cooling; we use the rates in [3]. We include other effects such as H line cooling and Compton cooling [28]. We use opacities from [29]; e.g., at $n \sim 10^{13}$ cm^{-3}, we take $\sim$8% cooling efficiency. Setting the heating rate equal to the cooling rate gives the critical temperature $T_c(n)$ below which heating dominates over all cooling mechanisms at a given gas core density n.

In Fig. 2 we compare $T_c(n)$ to typical evolution tracks in the temperature-density phase plane. We illustrate results for a range of WIMP masses from 1 GeV–10 TeV for a canonical 3×10^{-26} cm^3/ sec annihilation cross section. Since the heating rate scales as $\langle \sigma v \rangle / m_\chi$, these same curves equivalently apply to a variety of cross sections for a given WIMP mass.

The key result is that the evolution tracks and the critical temperature lines always cross, regardless of WIMP mass or H_2 fraction: this is a robust result. Once the core density reaches this crossing point, the DM heating dominates over cooling inside the core and changes its evolution: most of the annihilation energy remains inside the core and heats it up to the point where further collapse of the core becomes difficult. The protostellar core is prevented from cooling and collapsing further.

Since DM heating is independent of temperature while the H_2 cooling rate increases with temperature, the crossing point is stable against temperature changes at constant density and composition.

Our results were obtained for two values of the H_2 fraction: (i) the value given by the simulations without DM, and (ii) 100% molecular hydrogen. The latter case is motivated by the additional electrons produced by DM annihilation, which can increase the H_2 fraction and enhance the cooling rate. For 100 GeV WIMPs, the distinction is irrelevant, because the DM heating becomes important at high gas densities, which are already 100% molecular. At $m_\chi = 1$ GeV, the distinction matters. The crossing point for standard H_2 fraction is at low densities,

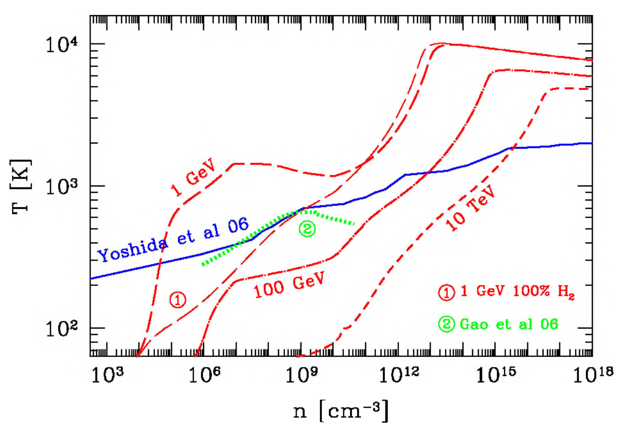

FIG. 2 (color online). Comparison of critical temperature [dashed (red) lines] to typical evolution tracks in the temperature-density phase plane. The solid (blue) and dotted (green) lines show the protostellar gas evolution from simulations of [21,29], respectively. The dashed (red) lines mark $T_c(n)$ for (i) $m_\chi = 1$ GeV with H_2 density from simulations, (ii) $m_\chi = 1$ GeV assuming 100% H_2, (iii) $m_\chi = 100$ GeV, and (iv) $m_\chi = 10$ TeV. At the crossing point of the solid (blue) or dotted (green) and dashed (red) lines, DM heating dominates over cooling in the core's evolution.

around $n \sim 10^5$ cm^{-3}, in agreement with [15]. At 100% H_2 fractions, heating dominates later, once $n \sim 10^9$ cm^{-3}.

Discussion.—Our main conclusion is that the standard picture of the formation of the first stars is drastically modified by WIMP dark matter annihilation. The DM annihilation provides a heat source that exceeds any cooling mechanism and thereby hinders the further collapse of the protostar.

For $m_\chi = 100$ GeV (1 GeV), the stalling of the protostellar collapse due to DM heating takes place when the gas density reaches $n > 10^{13}$ cm^{-3} ($n > 10^9$ cm^{-3}). At this point the DM density is 2% (10%) of the gas density in the core, the size of the core is $\sim$17 a.u. ($\sim$960 a.u.), its mass is $\sim 0.6 M_\odot$ ($\sim 0.11 M_\odot$), $f_Q \sim 2/3$, and the energy produced by DM heating is $\sim 140 L_\odot$ ($\sim 835 L_\odot$).

We propose that a new type of object is created, a "dark star" supported by DM annihilation rather than fusion. One crucial question is how long such a phase of stellar evolution lasts. Dark stars could last as long as the DM annihilation time scale,

$$\begin{aligned}\tau_e &= m_\chi / (\rho_\chi \langle \sigma v \rangle) \\ &\simeq 0.6\ \mathrm{Gyr} (n/10^{13}\ \mathrm{cm}^{-3})^{-0.8} (m_\chi / 100\ \mathrm{GeV}) (\sigma v / 3 \\ &\quad \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1})^{-1}.\end{aligned}$$

For our canonical case, $\tau_e \sim 600$ Myr for $n = 10^{13}$ cm^{-3} ($\sim$15 Myr for $n = 10^{15}$ cm^{-3}). By comparison, the entire time scale for collapse (without considering DM annihilation) is $\sim$1 Myr at $z = 50$ or 100 Myr at $z = 15$; the dynamical time at the high densities considered here is $\ll 10^3$ yr. Dark stars could last longer than τ_e if, as the DM annihilates away, the DM hole in the central core is filled in again. DM further out could also continue to heat the core.

Further work is required to address the evolution of these objects; we here briefly speculate as to possible outcomes. One possibility is that dark stars are stable for a long time period, they never reach the main sequence, and they still persist today. A second possibility is a shorter dark star phase, during which the gas core is in a state of quasihydrostatic equilibrium. (For our 100 GeV case, both the surface gravity and the hydrostatic force per unit mass from the pressure gradient are of the same order of magnitude, $\sim 10^{-3}$ cm/s^2.) Outer material would continue to accrete onto the quasihydrostatic core [30], probably accompanied by the formation of an accretion shock. Once the core's central temperature reaches $\sim 10^6$ K, deuterium burning and a proton-proton chain might start. The star would finally reach the zero-age main sequence. In this scenario, fusion would be delayed rather than blocked. A third possibility is that the core's contraction slows down as a consequence of DM heating, and yet the core continues to contract further. Then DM heating would continue to dominate over cooling mechanisms at ever higher baryon densities.

The effects of a dark star phase of stellar evolution could be dramatic. The reionization of the intergalactic medium could be quite different, as would be the production of heavy elements required to form all future generations of stars. We clearly need to recompute stellar structure with this new heat source, to see how different dark stars would look from ordinary fusion-driven stars. It is possible, e.g., that dark stars are luminous but at lower temperatures, and that reionization via UV radiation is possible but delayed. Perhaps the discrepancy between measurements of σ_8 by WMAP3 and in Lyman-α could be resolved.

DM heating may also alter the mass of the first stars. Even without DM heating, the mass is uncertain. References [21,31] explored possibilities for the accretion of baryons onto the protostar (disk vs spherical as well as sensitivity to cosmology) and found great uncertainty as to the final stellar mass. DM heating might produce radiation at the Eddington luminosity whose pressure prevents further accretion, thus leading to lower mass stars than in the standard picture. Alternatively, the initial protostellar object may be large, and dark stars might accrete enough material to form large black holes [32,33] en route to building the as yet unexplained $10^9 M_\odot$ black holes observed at $z \sim 6$.

If dark stars are luminous but differ from the standard model of the first stars (e.g., shine at lower temperatures), then the James Webb Space Telescope could in principle find them (at $z \sim 10$). In addition, DM annihilation products such as neutrinos might be detectable and teach us about the nature of WIMPs. Current detectors do not have the angular resolution to identify an individual dark star at $z > 10$ (the νs would add to the extragalactic background and provide limits at best). However, they might be able to individually identify today's adiabatically contracted remnants of the $10^6 M_\odot$ DM halos that were once sites of Pop III star formation.

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