Dark Stars: the First Stars in the Universe may be powered by Dark Matter Heating

Katherine Freese*, Peter Bodenheimer†, Paolo Gondolo** and Douglas Spolyar‡

*Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109
†Astronomy Dept., University of California, Santa Cruz, CA 95064
**Physics Dept., University of Utah, Salt Lake City, UT 84112
‡Physics Dept., University of California, Santa Cruz, CA 95064

Abstract. A new line of research on Dark Stars is reviewed, which suggests that the first stars to exist in the universe were powered by dark matter heating rather than by fusion. Weakly Interacting Massive Particles, which may be there own antipartmers, collect inside the first stars and annihilate to produce a heat source that can power the stars. A new stellar phase results, a Dark Star, powered by dark matter annihilation as long as there is dark matter fuel.

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INTRODUCTION

The first stars to form in the universe, at redshifts $z \sim 10-50$, may be powered by dark matter annihilation for a significant period of time [1]. We have dubbed these objects "Dark Stars."

Weakly Interacting Massive Particles (WIMPs) are the best motivated dark matter candidates. WIMP annihilation in the early universe provides the right abundance today to explain the dark matter content of our universe. This same annihilation process will take place at later epochs in the universe wherever the dark matter density is sufficiently high to provide rapid annihilation. The first stars to form in the universe are a natural place to look for significant amounts of dark matter annihilation, because they form at the right place and the right time. They form at high redshifts, when the universe was still substantially denser than it is today, and at the high density centers of dark matter haloes.

The first stars form inside dark matter (DM) haloes of $10^6 M_\odot$ (for reviews see e.g. [2, 3, 4, 5]; see also [6, 7].) One star is thought to form inside one such DM halo. The first stars may play an important role in reionization, in seeding supermassive black holes, and in beginning the process of production of heavy elements in later generations of stars.

It was our idea to ask, what is the effect of the DM on these first stars? We studied the behavior of WIMPs in the first stars, and found that they can radically alter the stellar evolution. The annihilation products of the dark matter inside the star can be trapped and deposit enough energy to heat the star and prevent it from further collapse. A new stellar phase results, a Dark Star, powered by DM annihilation as long as there is DM fuel, for millions to billions of years.

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Weakly Interacting Dark Matter

WIMPs are natural dark matter candidates from particle physics. These particles, if present in thermal abundances in the early universe, annihilate with one another so that a predictable number of them remain today. The relic density of these particles is

$$\Omega_\chi h^2 = (3\times 10^{-26}\mathrm{cm}^3/\mathrm{sec})/\langle\sigma v\rangle_{ann} \quad (1)$$

where the annihilation cross section $\langle\sigma v\rangle_{ann}$ of weak interaction strength automatically gives the right answer, near the WMAP [8] value $\sim 23\%$. This coincidence is known as "the WIMP miracle" and is the reason why WIMPs are taken so seriously as DM candidates. The best WIMP candidate is motivated by Supersymmetry (SUSY): the lightest neutralino in the Minimal Supersymmetric Standard Model (see the reviews by [9, 10, 11, 12]).

This same annihilation process is also the basis for DM indirect detection searches. The first paper discussing annihilation in stars was [13]; the first papers suggesting searches for annihilation products of WIMPs in the Sun were by Silk *et al* [14]; and in the Earth by Freese [15] as well as Krauss, Srednicki and Wilczek [16]. Other studies of WIMPs in today's stars include [17, 18, 19, 20]. This talk reviews the study of WIMP annihilation as a heat source for the first stars.

As our canonical parameter values, we take $m_\chi = 100\mathrm{GeV}$ for the WIMP mass and $\langle\sigma v\rangle_{ann} = 3\times 10^{-26}\mathrm{cm}^3/\mathrm{sec}$ for the annihilation cross section but consider a variety of masses and cross sections.

THREE CRITERIA FOR DARK MATTER HEATING

WIMP annihilation produces energy at a rate per unit volume

$$Q_{\mathrm{ann}} = \langle\sigma v\rangle_{ann}\rho_\chi^2/m_\chi \simeq 10^{-29}\frac{\mathrm{erg}}{\mathrm{cm}^3/\mathrm{s}}\ \frac{\langle\sigma v\rangle}{(3\times 10^{-26}\mathrm{cm}^3/\mathrm{s})}\left(\frac{n}{\mathrm{cm}^{-3}}\right)^{1.6}\left(\frac{100\mathrm{GeV}}{m_\chi}\right) \quad (2)$$

where ρ_χ is the DM energy density inside the star and n is the stellar hydrogen density. Paper I [1] outlined the three key ingredients for Dark Stars: 1) high dark matter densities, 2) the annihilation products get stuck inside the star, and 3) DM heating wins over other cooling or heating mechanisms. These same ingredients are required throughout the evolution of the dark stars, whether during the protostellar phase or during the main sequence phase.

First criterion: High Dark Matter density inside the star. One can see from Eq.(2) that the DM annihilation rate scales as WIMP density squared, because two WIMPs must find each other to annihilate. Thus the annihilation is significant wherever the density is high enough. Dark matter annihilation is a powerful energy source in these first stars (and not in today's stars) because the dark matter density is high. First, DM densities in the early universe were higher by $(1+z)^3$. Second, the first stars form exactly in the centers of DM haloes where the densities are high (as opposed to today's stars which are scattered throughout the disk of the galaxy rather than at the Galactic Center). We assume for our standard case that the DM density inside the $10^6 M_\odot$ DM halo initially

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has an NFW (Navarro, Frenk & White [21]) profile for both DM and gas, which has substantial DM in the center of the halo. Third, a further DM enhancement takes place in the center of the halo: as the protostar forms, it deepens the potential well at the center and pulls in more DM as well. We have computed this enhancement in several ways [1] (see also [22]); most recently we performed an exact calculation [23]. Fourth, at later stages, we also consider possible further enhancement due to capture of DM into the star (discussed below).

Second Criterion: Dark Matter Annihilation Products get stuck inside the star. In the early stages of Pop III star formation, when the gas density is low, most of the annihilation energy is radiated away [24]. 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. While neutrinos escape from the cloud without depositing an appreciable amount of energy, electrons and photons can transmit energy to the core. We have computed estimates of this fraction f_Q as the core becomes more dense. Once $n \sim 10^{11}{\rm cm}^{-3}$ (for 100 GeV WIMPs), e^- and photons are trapped and we can take $f_Q \sim 2/3$.

Third Criterion: DM Heating is the dominant heating/cooling mechanism in the star. We find that, for WIMP mass $m_\chi = 100{\rm GeV}$ (1 GeV), a crucial transition takes place when the gas density reaches $n > 10^{13}{\rm cm}^{-3}$ ($n > 10^9{\rm cm}^{-3}$). Above this density, DM heating dominates over all relevant cooling mechanisms, the most important being H_2 cooling [25].

Figure 5 shows evolutionary tracks of the protostar in the temperature-density phase plane with DM heating included (Yoshida et al. [26]), for two DM particle masses (10 GeV and 100 GeV). Moving to the right on this plot is equivalent to moving forward in time. Once the black dots are reached, DM heating dominates over cooling inside the star, and the Dark Star phase begins. The protostellar core is prevented from cooling and collapsing further. The size of the core at this point is ~ 17 A.U. and its mass is $\sim 0.6 M_\odot$ for 100 GeV mass WIMPs. A new type of object is created, a Dark Star supported by DM annihilation rather than fusion.

BUILDING UP THE MASS

We have found the stellar structure of the dark stars (hereafter DS) [27]. They accrete mass from the surrounding medium. In our paper we build up the DS mass as it grows from $\sim 1 M_\odot$ to $\sim 1000 M_\odot$. As the mass increases, the DS radius adjusts until the DM heating matches its radiated luminosity. We find polytropic solutions for dark stars in hydrostatic and thermal equilibrium. We build up the DS by accreting $1 M_\odot$ at a time with an accretion rate of $2 \times 10^{-3} M_\odot/{\rm yr}$, always finding equilibrium solutions. We find that initially the DS are in convective equilibrium; from $(100-400) M_\odot$ there is a transition to radiative; and heavier DS are radiative. As the DS grows, it pulls in more DM, which then annihilates. We continue this process until the DM fuel runs out at $M_{DS} \sim 800 M_\odot$ (for 100 GeV WIMPs). Figure 6 shows the stellar structure.

One can see "the power of darkness:" although the DM constitutes a tiny fraction ($< 10^{-3}$) of the mass of the DS, it can power the star. The reason is that WIMP annihilation is a very efficient power source: 2/3 of the initial energy of the WIMPs is

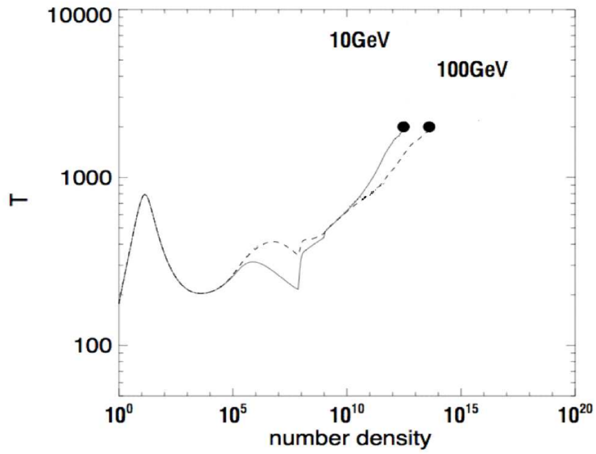

FIGURE 1. Temperature (in degrees K) as a function of hydrogen density (in cm^{-3}) for the first protostars, with DM annihilation included, for two different DM particle masses (10 GeV and 100 GeV). Moving to the right in the figure corresponds to moving forward in time. Once the "dots" are reached, DM annihilation wins over H2 cooling, and a Dark Star is created.

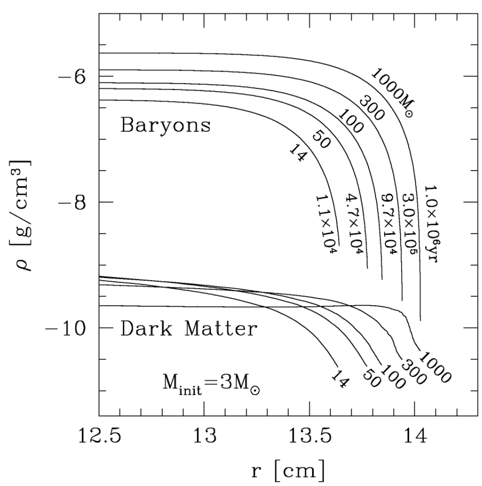

FIGURE 2. Evolution of a dark star (n=1.5) as mass is accreted onto the initial protostellar core of 3 $M_{\odot}$. The set of upper (lower) curves correspond to the baryonic (DM) density profile at different masses and times. Note that DM constitutes $< 10^{-3}$ of the mass of the DS.

converted into useful energy for the star, whereas only 1% of baryonic rest mass energy is useful to a star via fusion.

RESULTS AND PREDICTIONS

Our final result [27] is very large first stars; e.g., for 100 GeV WIMPs, the first stars have $M_{DS} = 800 M_{\odot}$. Once the DM fuel runs out inside the DS, the star contracts until it

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reaches 10^8K and fusion sets in. A possible end result of stellar evolution will be large black holes. The Pair Instability SN [29] that would be produced from 140-260 $M_\odot$ stars (and whose chemical imprint is not seen) would not be as abundant. Indeed this process may help to explain the supermassive black holes that have been found at high redshift ($10^9 M_\odot$ BH at z=6) and are, as yet, unexplained [30, 31]. The stars are very bright, $\sim 10^6 L_\odot$, and relatively cool, (6000-10,000)K (as opposed to standard Pop III stars whose surface temperatures exceed $30,000K$). One can thus hope to find DS and differentiate them from standard Pop III stars.

LATER STAGES: CAPTURE

The dark stars will last as long as the DM fuel inside them persists. The original DM inside the stars runs out in about a million years. However, as discussed in the next paragraph, the DM may be replenished by capture, so that the DS can live indefinitely due to DS annihilation. We suspect that the DS will eventually leave their high density homes in the centers of DM haloes, especially once mergers of haloes with other objects takes place, and then the DM fuel will run out. The star will eventually be powered by fusion. Whenever it again encounters a high DM density region, the DS can capture more DM and be born again.

The new source of DM in the first stars is capture of DM particles from the ambient medium. Any DM particle that passes through the DS has some probability of interacting with a nucleus in the star and being captured. The new particle physics ingredient required here is a significant scattering cross section between the WIMPs and nuclei. Whereas the annihilation cross section is fixed by the relic density, the scattering cross section is a somewhat free parameter, set only by bounds from direct detection experiments. Two simultaneous papers [32, 33] found the same basic idea: the DM luminosity from captured WIMPs can be larger than fusion for the DS. Two uncertainties exist here: the scattering cross section, and the amount of DM in the ambient medium to capture from. DS studies following the original papers that include capture have assumed (i) the maximal scattering cross sections allowed by experimental bounds and (ii) ambient DM densities that are never depleted. With these assumptions, DS evolution models with DM heating after the onset of fusion have now been studied in several papers [34, 35, 36]. Studies of effects on reionization have been looked at by [37].

In short, the first stars to form in the universe may be Dark Stars powered by DM heating rather than by fusion. Our work indicates that they may be very large ($800 M_\odot$ for 100 GeV mass WIMPs). Once DS are found, one can use them as a tool to study the properties of WIMPs.

CONCLUSION

95% of the mass in galaxies and clusters of galaxies is in the form of an unknown type of dark matter. One of the key properties of WIMP candidates is its annihilation cross section, yielding the proper relic density today. As a consequence of this annihilation, the first stars in the universe may provide another avenue to test the DM hypothesis. These stars may be powered by DM annihilation, and one can look for them in upcoming telescopes. It is an exciting prospect to discover a new type of star powered by the dark matter in the universe.

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