PROCEEDINGS OF SCIENCE

Dark Stars: Begynnelsen

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The first phase of stellar evolution in the history of the universe may be Dark Stars, powered by dark matter heating rather than by fusion. Weakly interacting massive particles, which are their own antiparticles, can annihilate and provide an important heat source for the first stars in the universe. This and the following contribution present the story of Dark Stars. In this first part, we describe the conditions under which dark stars form in the early universe: 1) high dark matter densities, 2) the annihilation products get stuck inside the star, and 3) dark matter heating wins over all other cooling or heating mechanisms.

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We have studied the effect of Dark Matter particles on the very first stars to form in the universe. We have found a new phase of stellar evolution: the first stars to form in the universe may be "Dark Stars," powered by dark matter annihilation rather than nuclear fusion. We first reported on this work in ([1]).

The Dark Matter particles we considered are Weakly Interacting Massive Particles (WIMPs) (such as the Lightest Supersymmetric Particle), which are one of the major motivations for building the Large Hadron Collider at CERN that will begin taking data very soon. These particles are their own antiparticles; they annihilate among themselves in the early universe, leaving the correct relic density today to explain the dark matter in the universe. These particles will similarly annihilate wherever the DM density is high. The first stars are particularly good sites for annihilation because they form at high redshifts (density scales as $(1+z)^3$) and in the high density centers of DM haloes. The first stars form at redshifts $z \sim 10-50$ in dark matter (DM) haloes of $10^6 M_\odot$ (for reviews see e.g. [2, 3, 4]; see also [5].) One star is thought to form inside one such DM halo.

As canonical values for the particle peoperties, we will use the standard annihilation cross section, $\langle \sigma v \rangle = 3 \times 10^{-26}\mathrm{cm}^3/\mathrm{sec}$, and a particle mass $m_\chi = 100$ GeV; but we will also consider a broader range of masses and cross-sections. In ([1]) we found that DM annihilation provides a powerful heat source in the first stars, a source so intense that its heating overwhelms all cooling mechanisms; subsequent work has found that the heating dominates over fusion as well once it becomes important at later stages (see accompanying contribution [6]). Paper I ([1]) suggested that the very first stellar objects might be "Dark Stars," a new phase of stellar evolution in which the DM – while only a negligible fraction of the star's mass – provides the power source for the star through DM annihilation.

1. Three Criteria

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

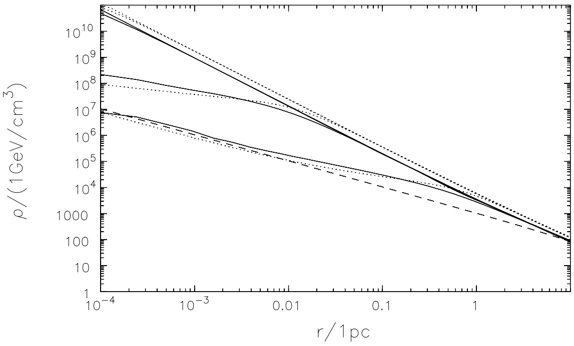

Figure 1: Adiabatically contracted DM profiles in the first protostars for an initial NFW profile (dashed line) using (a) the Blumenthal method (dotted lines) and (b) an exact calculation using Young's method (solid lines), for $M_{\mathrm{vir}} = 5 \times 10^7 M_\odot$, $c = 2$, and $z = 19$. The four sets of curves correspond to a baryonic core density of $10^4, 10^8, 10^{13}$, and $10^{16}\mathrm{cm}^{-3}$. The two different approaches to obtaining the DM densities find values that differ by less than a factor of two.

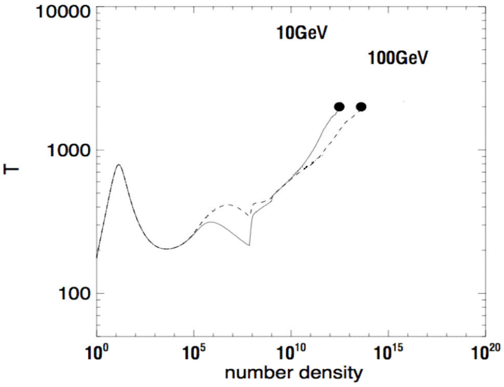

Figure 2: Temperature (in degrees K) as a function of hydrogen density (in cm^{-3}) for the first protostars, with DM annihilation included, for two different DM particle masses (10 GeV and 100 GeV). Moving to the right in the figure corresponds to moving forward in time. Once the “dots” are reached, DM annihilation wins over H2 cooling, and a Dark Star is created.

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. To find the DM density profile, we start with an overdense region of $\sim 10^6 M_\odot$ with an NFW ([7]) profile for both DM and gas, where the gas contribution is 15% of that of the DM. Originally we used adiabatic contraction ($M(r)r$ = constant) ([8]) and matched onto the baryon density profiles given by [9] and [10] to obtain DM profiles. This method is overly simplified: it considers only circular orbits of the DM particles. Our original DM profile matched that obtained numerically in [9] with $\rho_\chi \propto r^{-1.9}$, for both their earliest and latest profiles; see also [11] for a recent discussion. Subsequent to our original work, we have done an exact calculation (which includes radial orbits) ([12]) and found that our original results were remarkably accurate, to within a factor of two. Our resultant DM profiles are shown in Fig. 1. At later stages, we also consider possible further enhancements due to capture of DM into the star (see [6]).

Second Criterion: The dark matter annihilation products get stuck inside the star. WIMP annihilation produces energy at a rate per unit volume $Q_{\rm ann} = \langle\sigma v\rangle \rho_\chi^2/m_\chi \simeq 1.2\times 10^{-29}{\rm erg/cm^3/s}\ (\langle\sigma v\rangle/(3\times10^{-26}{\rm cm^3/s}))(n/{\rm cm^{-3}})^{1.6}(m_\chi/(100{\rm GeV}))^{-1}$. In the early stages of Pop III star formation, when the gas density is low, most of this energy is radiated away ([13]). 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: Dark matter heating is the dominant heating/cooling mechanism in the star. We find that, for WIMP mass $m_\chi = 100$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 ([14]).

Figure 2 shows evolutionary tracks of the protostar in the temperature-density phase plane with DM heating included ([15]), 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.

References

[1] D. Spolyar, K. Freese, & P. Gondolo astro-ph/0705.0521, 2008, *Phys. Rev. Lett.*, 100, 051101

[2] E. Ripamonti & T. Abel astro-ph/0507130.

[3] R. Barkana & A. Loeb 2001, *Phys. Rep.*, 349, 125

[4] V. Bromm & R. B. Larson 2004, *ARAA*, 42, 79

[5] N. Yoshida, K. Omukai, L. Hernquist & T. Abel 2006, *ApJ*, 652, 6

[6] D. Spolyar et al, these proceedings.

[7] J. F. Navarro, C. S. Frenk & S. D. M. White 1996, *ApJ*, 462, 563

[8] G. R. Blumenthal, S. M. Faber, R. Flores & J. R. Primack 1986, *ApJ*, 301, 27

[9] T. Abel, G. L. Bryan & M. L. Norman 2002, *Science*, 295, 93

[10] L. Gao, T. Abel, C. S. Frenk, A. Jenkins, V. Springel & N. Yoshida 2007, *MNRAS*. 378, 449

[11] A. Natarajan, J. Tan, & B. O'Shea 2008, arXiv:0807.3769 [astro-ph]

[12] K. Freese, P. Gondolo, J Sellwood & D. Spolyar 2008, arxiv:0805.3540 [astro-ph]

[13] E. Ripamonti, M. Mapelli & A. Ferrara 2007, *MNRAS*, 375, 1399

[14] D. Hollenbach & C. F. McKee 1979, *ApJ* Suppl., 41, 555

[15] N. Yoshida, K. Freese, P. Gondolo, & D. Spolyar 2008, in preparation