Asymmetric dark matter may alter the evolution of low-mass stars and brown dwarfs

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We study energy transport by asymmetric dark matter in the interiors of very low-mass stars and brown dwarfs (BD). Our motivation is to explore astrophysical signatures of asymmetric dark matter, which otherwise may not be amenable to conventional indirect dark matter searches. In viable models, the additional cooling of very low-mass stellar cores can alter stellar properties. Asymmetric dark matter with mass $\lesssim 15 \text{ GeV}$ and a spin-dependent (spin-independent) cross section of $\sigma^\text{SD}_{p} \sim 10^{-37} \text{ cm}^2$ (\(\sigma^\text{SI}_{p} \sim 10^{-46} \text{ cm}^2\)) can increase the minimum mass of main sequence hydrogen burning, partly determining whether or not the object is a star at all. Similar dark matter candidates reduce the luminosities of low-mass stars and accelerate the cooling of brown dwarfs. Such light dark matter is of particular interest given results from the DAMA, CoGeNT, and CRESST dark matter searches. We discuss possibilities for observing dark matter effects in stars in the solar neighborhood, globular clusters, and, of particular promise, local dwarf galaxies, among other environments, as well as exploiting these effects to constrain dark matter properties.

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Overwhelming evidence indicates that a form of non-baryonic matter constitutes the majority of mass in the Universe. The unknown nature of the dark matter (DM) is a fundamental problem in cosmology and particle physics. Among DM candidates, weakly-interacting massive particles (WIMPs), particularly the lightest supersymmetric partners in supersymmetric theories, have garnered the most attention [1]. We study the effects of asymmetric dark matter (ADM) on the evolution of very low-mass (VLM) stars and brown dwarfs (BD). We show that stars with masses $M \lesssim 0.15M_\odot$ and BDs just below the minimum mass for a hydrogen-burning main sequence (MS) star, $M \gtrsim 0.05M_\odot$, may have their evolution significantly altered by the accumulation of DM.

ADM has a relic asymmetry, so it does not annihilate as thermal relic WIMPs do. Consequently, ADM is not amenable to indirect detection via observations of annihilation products from astrophysical sources [2]. Our result suggests a future indirect identification method for ADM in astrophysical sources. In the present context, the relic asymmetry allows stars to collect large amounts of DM without the accumulation being moderated by annihilation [3, 4]. ADM models offer a possible solution for the DM and baryon densities of the Universe being of the same order [4, 10]. ADM models are relevant to DM particles with masses $M \lesssim 15 \text{ GeV}$, lower than typical WIMPs, and interest in ADM has been fueled by possible direct detection signals indicating low-mass DM by the DAMA [17], CoGeNT [18, 19] and CRESST-II [20] experiments [21, 22] (though challenged by Xenon-10 limits, Ref. 23).

It has long been recognized that DM could accumulate in the Sun (and other stars) subtly altering its properties, particularly solar neutrino fluxes [4, 18]. The scenario is simple. As the star orbits in the DM halo, some DM particles scatter off stellar nuclei and become bound to the star. The captured DM particles can be non-negligible contributors to energy transport in the stellar interior.

DM with $M \lesssim 15 \text{ GeV}$ is captured by stars at a rate

$$C_\star \approx \frac{C_{\odot}^{\text{SI,SD}}}{\odot} \frac{\rho_\star}{0.4 \text{ GeV cm}^{-3}} \frac{\sigma_p}{10^{-43} \text{ cm}^2} \times \left( \frac{v_\text{esc}}{618 \text{ km s}^{-1}} \right)^2 \left( \frac{270 \text{ km s}^{-1}}{v_c} \right) \left( \frac{M_\star}{M_\odot} \right), \tag{1}$$

where $M_\star$ is stellar mass, $\rho_\star$ is the DM density in the star’s vicinity, $\sigma_p$ is the cross-section for ADM-proton scattering, $v_\text{esc}$ is the stellar escape speed, and $v_c$ is the typical speed at infinity of infalling DM particles. The coefficients $C_{\odot}^{\text{SI}} \approx 7 \times 10^{22} \text{s}^{-1}$ and $C_{\odot}^{\text{SD}} \approx 5 \times 10^{21} (5 \text{ GeV}/M_\odot) \text{s}^{-1}$ give the rates in the Sun due to spin-independent (SI) and spin-dependent (SD) scattering respectively [22]. We include the $M_\star$ dependence in $C_{\odot}^{\text{SI}}$. $C_{\odot}^{\text{SD}}$ is a weak function of $M_\star$. In the SI case, we take the scattering cross section on a nucleus with mass $M_N$ and mass number $A$ to be $\sigma_N = \sigma_p^\text{SI} A^2 M_N^2 (M_\star + m_p)^2/(M_\star + M_N)^2 m_p^2$, where $m_p$ is the proton mass. We provide Eq. (1) for convenience, but calculate time-dependent capture rates using the full formula from [23] as described in Ref. 28.

VLM stars and BDs are interesting DM laboratories for several reasons. First, dark matter capture rates depend upon stellar structure only insomuch as $v_\text{esc}$ does. In VLM stars, mass is proportional to radius so VLM stars have similar escape speeds to the Sun and capture nearly the same amount of DM per unit mass. Second, stellar luminosity scales with mass roughly as $L \propto M_x^3$ for VLM stars, so a $M_\star \sim 0.1M_\odot$ star radiates only $L \sim 10^{-3}L_\odot$, and DM needs to transport a relatively small energy flux to alter the stellar evolution. Third, VLM stars have core
temperatures many times lower than the Sun and nuclear burning rates in this regime are rapidly-varying functions of temperature, so small temperature changes have large effects on luminosity. These considerations suggest that DM energy transport may dramatically alter VLM stars.

The mean free path of captured DM exceeds stellar radii, so DM energy transport is non local. Nevertheless, we can make an order-of-magnitude estimate of the energy flux transmitted by DM from the stellar core by considering this transport to be diffusive, with an effective diffusion coefficient \( \eta' \sim \eta(\sigma_p/\sigma_c)^2 \), where \( \eta \sim (1/n_p \sigma_p) \sqrt{kT_c/M_x} \) is the standard for diffusive transport \([29]\). The cross-section for which the star is optically thick is \( \sigma_c \equiv (m_p/M_x)\pi R_*^2 \). The factors \((\sigma_p/\sigma_c)^2\) account for the facts that DM orbits span far less than a mean free path and DM particles scatter only after many orbits. Using \( \eta' \) and estimating the temperature gradient as \( dT/dr \sim T_c/R_* \), the rate at which DM removes energy from the stellar core is,

\[
\frac{L_\lambda}{10^{-3}L_\odot} \sim \frac{1.6 \times 10^{13}}{M_x} \left( \frac{\sigma_p^{SD}}{10^{-37} \text{ cm}^2} \right) \left( \frac{N_x}{N_p} \right) \sqrt{\frac{m_p}{M_x}}. \tag{2}
\]

Eq. (2) includes only SD scattering for simplicity, \( N_x \) is the number of captured DM particles, and \( N_p \) is the number of protons. A luminosity of \( L_\lambda \sim 10^{-3}L_\odot \) is typical for the \( M_x \sim 0.1M_\odot \) star we have assumed.

The energy flux carried by DM is of order the stellar luminosity \( L_\star \sim 10^{-3}L_\odot \) if \( N_x \sim 10^{-13}N_p \sim 10^{43} \). A cross-section of \( \sigma_p^{SD} = 10^{-37} \text{ cm}^2 \) yields a capture rate of \( C_x \sim 5 \times 10^{36} \text{ s}^{-1} \). Assuming a lifetime \( \tau \sim 10^{10} \text{ yr} \), then \( N_x \sim 10^{44} \), so large effects are possible in ADM models. We have computed the DM heat transfer rate within \( n = 3/2 \) polytropic stellar models, appropriate for fully convective stars with \( M_x \sim 0.1M_\odot \) [30], and confirmed this approximate result. These approximations are not self-consistent; however, they provide strong indications that ADM effects may be non-negligible. DM effects are dramatic in environments with large capture rates. We parametrize environment with \( \Gamma_B \), the ratio of the capture rate of DM to the standard capture rate in the solar neighborhood. As we discuss below, environments with \( \Gamma_B \gg 1 \) are known to exist and \( \Gamma_B \gg 1 \) may effectively be realized in the solar neighborhood.

We perform a self-consistent stellar evolution calculation by computing capture rates as in Ref. [28] and including DM heat transport in the Modules for Experiments in Stellar Astrophysics (MESA) software [31]. We base our models on the MESA VLM star models ([\( \S \) 7.1 of Ref. [31])). Ideally, one would calculate DM energy transport by solving the Boltzmann equation at each stage of stellar evolution [32], but this is computationally challenging and beyond our present scope. We adopt the approximations of Ref. [24], namely, that DM has an effective temperature \( T_c \), and that energy transport can be estimated from the first moment of the Boltzmann equation.

\[
\epsilon = 8 \sqrt{\frac{2}{\pi}} \frac{n_x \sigma_p^{SD} M_x}{(M_x + m_p)^2} \frac{f_H}{m_p} \left( \frac{m_p T_x + M_x T}{M_x m_p} \right)^2 (T - T_x), \tag{3}
\]

where \( n_x \) is the local DM number density, \( f_H = 0.71 \) is the local mass fraction in hydrogen, and \( T_x \) is fixed by requiring that there be no net energy transfer. In the case of SI scattering, one sums Eq. (3) over all nuclei. Eq. (3) has known shortcomings, but corrections are generally of order unity and there is no general treatment that can be incorporated into a stellar evolution model in a computationally-feasible manner [32]. Uncertainty associated with DM parameters is large, so this approximation should suffice for the present purpose.

In the interest of brevity, we quote detailed results for a fiducial model of ADM with \( M_x = 5 \text{ GeV} \) and \( \sigma_p^{SD} = 10^{-37} \text{ cm}^2 \), well below current limits [33]. However, we obtain similar results for SI cross-sections \( \sigma_p^{SI} \sim 10^{-40} \text{ cm}^2 \) due to the large cross sections for DM scattering on heavier elements, primarily He, C, O, Ne. Specifically, a model with \( M_x \sim 7 \text{ GeV} \) and \( \sigma_p^{SI} \sim 10^{-40} \text{ cm}^2 \) yields stellar evolution similar to our fiducial case and is of interest given indications of low-mass DM scattering by the DAMA [17] and CoGeNT [18,19] collaborations.
We account for possible loss of DM by evaporation from the stellar interior following Ref. [34], with the result that evaporation is negligible for DM masses $M_x \gtrsim 3\text{ GeV}$. This is slightly smaller than the evaporation mass from the Sun ($M_x \gtrsim 3.7\text{ GeV}$), primarily due to the cooler interiors of VLM stars.

Fig. 1 shows the evolution of central density $\rho_c$, and central temperature $T_c$, for VLM stars and BDs. This classic plot illustrates that a collapsing gas cloud of sufficiently low mass will achieve a maximum $T_c$ too meager to ignite hydrogen burning at a level that can halt gravitational collapse [35]. Maximum $T_c$ is achieved when pressure support becomes dominated by electron degeneracy. Objects with $M_x \gtrsim 0.08M_\odot$ halt contraction when hydrogen burning begins and enter the stellar main sequence, enjoying long MS lifetimes. Lower-mass objects continue to contract and cool, becoming BDs. In Fig. 1, we compare standard stellar evolution to evolution including DM cooling in our fiducial ADM model with a capture rate boosted by $\Gamma_B = 10^3$. In the DM models, the additional cooling causes degeneracy to be achieved at lower densities and temperature maxima are reduced at fixed stellar mass. Consequently, the minimum mass for MS H-burning increases by $\sim 15\%$.

We emphasize, with regard to Fig. 1, that the primary effect of ADM cooling is to drive the stellar core to degeneracy at a lower density. Once degeneracy sets in, DM energy transport becomes significantly less important and the degenerate core cools and contracts as in the standard evolution of a degenerate object [32, 36]. At all stages of evolution the stellar temperature profile is monotonic and the DM temperature closely tracks the baryonic temperature of the stellar core. Moreover, convective energy transport (see [30, 36]) remains an important channel for energy transport in the bulk of the stellar interiors in all of the models we have considered.

Important consequences of DM cooling are more apparent in Fig. 2, which depicts the evolution of luminosity for collapsing objects with $0.06 \leq M_x/M_\odot \leq 0.11 M_\odot$. In standard models, objects with $M_x \gtrsim 0.08M_\odot$ enter a long-lived phase of constant luminosity supported by core H-burning, the MS. Lower-mass objects cool and dim incessantly. In our DM model, objects with $M_x \lesssim 0.1 M_\odot$ dim continually and exhibit no constant-luminosity phase, so objects with $0.08 \lesssim M/M_\odot \lesssim 0.10$ are not MS stars. DM cooling effects are most dramatic just below the minimum MS mass, $M_x \approx 0.08 M_\odot$. In the standard case, such objects have their dimming delayed by non-negligible nuclear burning, yet nuclear reaction rates at such low temperatures are sensitive functions of temperature [30], so DM cooling quells this H-burning and drives these objects to lower luminosities. At $M = 0.08M_\odot$ the object with DM cooling is a factor of $\sim 15$ less luminous than its standard counterpart after $10^{10}\text{ yr}$. Notice that DM has little effect on objects with $M \lesssim 0.05M_\odot$ because these objects are never significantly affected by nuclear burning. Fig. 2 shows two additional cases of an $M = 0.08M_\odot$ object with $\Gamma_B = 10$ and $\Gamma_B = 10^2$, illustrating that DM cooling can have appreciable effects with more modest DM capture rates.

Figure 3 displays the shifts in the positions of stars on the HR diagram at several values of stellar mass after 10 Gyr of stellar evolution. The changes in effective temperature and luminosity are significant for a range of stellar masses from $0.05 \sim 0.10 M_\odot$. ADM accelerates the cooling and dimming of these stars, giving rise to a dearth of relatively luminous VLM stars and BDs.

It is possible to approximate the deficit of VLM stars. Assuming a fixed initial mass function and stellar metallicity, the change in the luminosity function of VLM stars and BDs is determined by the mass-luminosity relation, $L(M)$. We have approximated $L(M)$ using stellar models computed for masses separated by $\Delta M = 0.005 M_\odot$ between $M = 0.04M_\odot$ and $M = 0.12M_\odot$. Figure 3 shows the ratio of the luminosity function in our fiducial ADM scenario to a standard luminosity function for a stellar population after 10 Gyr of evolution. The significant deficit of VLM stars and BDs with luminosities $2 \times 10^{-5} L_\odot \lesssim L \lesssim 10^{-3} L_\odot$ is apparent. Furthermore, an excess number of dim BDs near $L \sim 10^{-5} L_\odot$ is also evident. This pile-up results from the accelerated dimming and cooling low-mass objects in the ADM model.
The effects of DM on VLM stars and BDs may have interesting consequences. To be sure, observing VLM stars and BDs is challenging; however, several operating and forthcoming astronomical facilities count observations of local and distant VLM stars and BDs among their science drivers including PanSTARRS [37], LSST [38], Euclid [39], TMT [47], GMT [48], and JWST [40]. At minimum, we have demonstrated that DM may have non-negligible effects on VLM stars and BDs, rendering them cooler and dimmer than otherwise at fixed age and chemical composition. The luminosity function of VLM stars and BDs should become significantly shallower from $10^{-3} \gtrsim L/L_\odot \gtrsim 10^{-5}$ and steepen at lower luminosities as indicated by Fig. 2 and Fig. 3. It may also be possible to identify seemingly anomalous VLM stellar or BD companions in studies of transits of more luminous stars. The strength of this effect should be correlated with environment: it is dramatic in regions of high-DM density and small in regions of low-DM density. This correlation may distinguish DM influences on stellar evolution from uncertainties in stellar modeling.

Dramatic effects generally require capture rates larger than standard rates in the solar neighborhood. High capture rates are possible in the solar neighborhood in particular models. A co-rotating disk of DM near the Galactic plane is a prediction of hierarchical galaxy formation and may provide a boost of $\Gamma_B \sim 10$ [41, 42]. Alternatively, DM with a significant self-interaction cross section can enhance capture rates equivalent to $\Gamma_B \sim 10^2$ or greater in the Sun and nearby stars [28, 29]. This suggests that observations of local VLM stars and BDs may constrain models of self-interacting ADM, though such constraints require careful modeling of stellar atmospheres and an exploration of stellar parameters, such as metallicity. Additionally, trace populations of VLM stars that were either (1) liberated in the disruption of merging dwarf galaxies during hierarchical formation of the Milky Way or (2) members of the halo star population that orbit through the Galactic Center would still be affected by ADM accumulated while these higher-density environments and be subject to the DM effects we describe.

Globular clusters (GC) are interesting environments in which to seek DM effects. The formation, evolution, and DM content of GCs are still under debate. However, GCs are many orders of magnitude denser than the solar neighborhood and have internal velocity dispersions a factor of $\geq 30$ less than the local value [43]. Moreover, the bounds on their DM contents are weak, with the ratio of DM-to-stellar mass $M_{DM}/M_s \lesssim 1$ [44]. Consequently, values of $M_{DM}/M_s$ well below those within reach of stellar kinematical studies would lead to values of $\Gamma_B \propto \rho_s/v \gg 1$ [see Eq. (1)]. This suggests that DM-induced alterations to stellar evolution may occur in GCs. If consensus ever formed around evidence for low-mass ADM, observations of stellar populations in GCs may reveal their past or present DM contents.

For fixed DM parameters, high capture rates should be realized in particular environments. One such environment is a Milky Way dwarf satellite galaxy. Consider the closest dwarf satellite, Segue I. Stellar kinematics indicate that the DM density in Segue I is $\sim 10^{-2}$ times the local value, while typical velocities are $10^2$ times lower [45], suggesting $\Gamma_B \propto \rho_s/v \sim 10^3 - 10^4$. VLM stars in dwarf galaxies are sensitive to low-mass ADM and may be within reach of future observatories such as JWST.

Interestingly, it may be possible to identify DM effects in the spectra of specific galaxies or GCs. Ref. [10] emphasized that spectral features due to Na and FeH are produced only by VLM stars and that the prevalence of these features reveals the contribution of VLM stars to the total galactic light. This suggests that stellar population synthesis studies may bear on the identification of DM and vice versa. Particular objects with kinematical or other evidence for high $\Gamma_B$ could be targeted for observation and the relative light contributed by VLM stars could limit the influence of DM on VLM stellar evolution. Alternatively, though more speculatively, it is thought that the first generations of stars formed in the inner regions of early-forming dark matter halos, environments with significantly higher DM density than should accompany contemporary star formation in the Milky Way, so galaxies in which a significant amount of star formation occurred at high redshift may have had low-mass stellar
populations markedly altered by DM.

Several advances must be made before DM constraints based on this effect could be realized. First and foremost, observations of VLM stars and BDs must be improved. Theoretically, it is necessary to implement computationally-efficient models of DM energy transport, to account for uncertainties in VLM stellar atmospheres, and explore stellar parameters, such as metallicity. We will report on these efforts in a detailed follow-up study. That ADM may have potentially-observable effects on VLM stars and BDs opens up intriguing new avenues for constraining DM and learning about the environments of stellar populations.

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