DARK MATTER BURNERS: PRELIMINARY ESTIMATES

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ABSTRACT

We show that a star orbiting close enough to an adiabatically grown supermassive black hole can capture a large number of weakly interacting massive particles (WIMPs) during its lifetime. WIMP annihilation energy release in low- to medium-mass stars is comparable with or even exceeds the luminosity of such stars due to thermonuclear burning. The excessive energy release in the stellar core may result in an evolution scenario different from what is expected for a regular star. The model thus predicts the existence of unusual stars within the central parsec of galactic nuclei. If found, such stars would provide evidence for the existence of particle dark matter. White dwarfs seem to be the most promising candidates to look for. The signature of a white dwarf burning WIMPs would be a very hot star with mass and radius characteristic for a white dwarf, but with luminosity exceeding the typical luminosity of a white dwarf by orders of magnitude \( \lesssim 50L_\odot \). A white dwarf with a highly eccentric orbit around the central black hole may exhibit variations in brightness correlated with the orbital phase.

Subject headings: black hole physics — elementary particles — radiation mechanisms: non-thermal — stars: general — stars: evolution — dark matter

1. INTRODUCTION

The nature of the non-baryonic dark matter, which dominates the visible matter by about 4:1, is perhaps the most interesting experimental challenge for contemporary particle astrophysics. A hint for a solution has been found in particle physics where the WIMPs arise naturally in supersymmetric extensions of the Standard Model (e.g., Haber & Kane 1985), among other possibilities. The WIMP is typically defined as a stable, electrically neutral, massive particle. Assuming that non-baryonic dark matter is dominated by WIMPs, the pair annihilation cross-section is restricted to provide the observed relic density (Jungman, Kamionkowski & Griest 1996, Bergström 2000). A pair of WIMPs can annihilate producing ordinary particles and \( \gamma \)-rays.

WIMPs are expected to form high density clumps according to N-body simulations of test particles with only gravitational interactions (Navarro, Frenk, & White 1997, Moore et al. 1999). The highest density “free space” dark matter regions occur for dark matter particles captured within the gravitational potential of adiabatically grown supermassive black holes (Gondolo & Silk 1999, Bertone & Merritt 2005). Higher dark matter densities are possible for dark matter particles captured inside of stars or planets. Any star close enough to an adiabatically grown supermassive black hole can capture a large number of WIMPs during a short period of time.

Such an idea has been first proposed by Salati & Silk (1989) and further developed by Bouquet & Salati (1989) who applied it to main-sequence stars. WIMP annihilation in stars may lead to considerable energy release in the stellar cores thus affecting the evolution and appearance of such stars. The model led to the conclusion of suppression of stellar core convection, thus predicting a concentration of stars in the Galactic center masquerading as cold red giants.

We perform order-of-magnitude estimates of WIMP capture rates for stars of various masses and evolution stages located in high density dark matter regions. We use current limits on WIMP-nucleus interaction and WIMP annihilation cross sections, as well as recent estimates of WIMP energy density near an adiabatically grown supermassive black hole. We argue that white dwarfs, fully burned stars without their own energy supply, are the most promising candidates to look for.

2. WIMP ACCUMULATION IN STARS

In a steady state the WIMP capture rate \( C \) is balanced by the annihilation rate (Griest & Seckel 1987)

\[
C = A N_X^2 \chi \tag{1}
\]

where \( N_X \) is the total number of WIMPs in the star,

\[
A = \langle \sigma v \rangle / V_{\text{eff}}, \tag{2}
\]

\[
V_{\text{eff}} = \pi^{3/2} r_X^3 \chi, \tag{3}
\]

\( \langle \sigma v \rangle \) is the velocity averaged WIMP pair annihilation cross-section, and the effective volume \( V_{\text{eff}} \) is determined by matching the core temperature \( T_c \) with the gravitational potential energy at the core radius \( r_X \) (assuming thermal equilibrium).

The total number of captured WIMPs is

\[
N_X = C \tau_{eq} \tanh(\tau_s / \tau_{eq}), \tag{4}
\]

where \( \tau_s \) is the star age, and the equilibrium time scale is given by

\[
\tau_{eq} = (CA)^{-1/2}. \tag{5}
\]

The number density distribution of WIMPs can be estimated as (Press & Spergel 1985, Griest & Seckel 1987).
In thermal equilibrium, the effective radius mined by the core temperature Bottino et al. 2002): for more details.

\[ n_X(r) = n_X^c \exp(-r^2/r_X^2), \]  

where \( n_X^c = N_X/V_{\text{eff}} \) is the central WIMP number density. In thermal equilibrium, the effective radius \( r_X = r_T \) is determined by the core temperature \( T_c \) and density \( \rho_c \):

\[ r_T = c \left( \frac{3T_c}{2\pi G\rho_c m_X} \right)^{1/2}, \]

where \( c \) is the speed of light, \( G \) is the gravitational constant, and \( m_X \) is the WIMP mass.

If the WIMP-nucleon scattering cross-section is large enough, then every WIMP crossing the star is captured and \( C \) saturates to a maximal value proportional to the star’s cross-sectional area \( \pi R_s^2 \), the WIMP velocity dispersion \( \bar{v} \), and the ambient WIMP energy density \( \rho_X \):

\[ C = \left( \frac{8}{3\pi} \right)^{1/2} \frac{\rho_X \bar{v}}{m_X} \left[ \zeta + \frac{3v_{\text{esc}}^2}{2\bar{v}^2} \right] \pi R_s^2, \]

where \( \zeta \) is taken to be 1.77, \( v_{\text{esc}} = \sqrt{2GM_s/R_s} \) is the escape velocity at the star’s surface, and \( M_s \) is the star mass.

Figures 1–3 show the mass–radius–capture rate diagrams for Helium stars. Lines are coded as in Figure 1.

Super-Kamiokande, which finds that \( \sigma_s \) is at most \( 10^{-38} \text{ cm}^2 \) (Super-Kamiokande 2004). In the following formulas we will use a generic cross-section \( \sigma_a \) to be substituted by \( \sigma_s \) or \( \sigma_s \) for spin-independent and spin-dependent interactions, correspondingly. If the star is entirely composed of nuclei with the atomic mass \( A_n \) (\( A_n = 1 \) for pure Hydrogen), we have for \( m_X \gg A_n m_p \):

\[ C = \left( \frac{8}{3\pi} \right)^{1/2} \frac{\rho_X \bar{v}}{m_X} \left[ \zeta + \frac{3v_{\text{esc}}^2}{2\bar{v}^2} \right] \sigma_a A_n^4 \frac{M_s}{A_n m_p}, \]

where \( m_p \) is the proton mass.

Eq. (8) gives an absolute upper limit on the capture rate. The allowable range of masses and radii at a given WIMP-nucleon scattering cross section can be obtained from eqs. (8) and (9):

\[ R_s \geq A_n^{3/2} \sqrt{\frac{\rho_X M_s}{\pi m_p}}, \]

Smaller radii are forbidden as the capture rate will exceed the upper limit given by eq. (8).

A star spends about 90% of its life burning hydrogen and most of the rest burning helium (Woosley et al. 2002, and references therein); the carbon, neon, oxygen, and silicon burning lasts about 1000 yr altogether. The star core temperature, matter density, the radius, and the mass, all change during the evolution cycle. The mass-loss by a star during its lifetime implies that stars with initial mass \( \geq 35 M_\odot \) and the solar metallicity to end their life as hydrogen-free objects of roughly \( 5 M_\odot \); early massive stars with essentially no metallicity will evolve differently and may retain a massive Hydrogen envelope even at later burning stages.

Figures 1–3 show the mass–radius–capture rate diagrams for \( m_X = 100 \text{ GeV} \), \( \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \), and WIMP velocity dispersion \( \bar{v} = 270 \text{ km s}^{-1} \). The value \( \rho_X = 10^{10} \text{ GeV cm}^{-3} \) corresponds to the maximal energy density allowed by the age of the supermassive black hole \( \sim 10 \text{ Gyr} \), and our selected values of \( \langle \sigma v \rangle \) and \( m_X \) Gondolo & Silk 1999, Bertone & Merritt 2005. The spin-dependent and spin-independent WIMP-nucleon scattering cross sections are taken as \( \sigma_s = 10^{-38} \text{ cm}^2 \) and \( \sigma_0 = 10^{-43} \).
cm², correspondingly. The series of dotted lines are calculated using eq. [9], and the numbers on the plots show the logarithm of WIMP capture rate log₁₀ C. The strong dashed line labeled “MS” in Figure[1] shows characteristics of the main sequence stars (Massey & Meyer[2001]), and the diamond symbol indicates sun-like star with $M = M_\odot$, $R = R_\odot$. The open circles on the main sequence show the stars of particular spectral type and the numbers show their luminosity log₁₀($L_\star/L_\odot$). The rectangular area outlined by the dashed line and labeled “WD” in Figure[3] shows the parameter range typical for white dwarfs. The solid line (eq. [10]) divides the diagram into “allowed” and “forbidden” parts. For any particular $M_\star$ and $R_\star$, the WIMP capture rate can be found from the grid provided by the dotted lines.

Table[1] shows the WIMP capture rate, WIMP accumulation, and other parameters for different star masses (1 − 75 $M_\odot$) and at different evolution stages. Spin-dependent WIMP accumulation is calculated for the Hydrogen burning stage and spin-independent WIMP accumulation is calculated for the Helium and Carbon burning stages. The star masses, radii, core temperatures and densities are taken from Woosley et al. (2002) and correspond to the particular burning stage. The $\tau_c$ column shows the duration of the corresponding burning cycle. The uppermost row in the Carbon burning stage table shows the parameters typical for a white dwarf where the core temperature is taken ad hoc. This does not affect the WIMP capture rate, however. Smaller annihilation cross section ($\sigma v \sim 3 \times 10^{-26}$ cm³ s⁻¹) will lead to a larger number of captured WIMPs, although this would not change the burning rate. Early massive low-metallicity stars can potentially accumulate the most numbers of WIMPs due to the presence of a large Hydrogen envelope. Such stars could capture WIMPs at greater rates due to the potentially larger spin-dependent WIMP-nucleon scattering cross-section. The WIMP number density may further increase during the sudden collapse of a massive star (ULLIO et al. 2001).

In steady state the annihilation rate is equal to the capture rate. The energy release due to the WIMP annihilation in the star core is

$$L_\star \sim 1.6 \times 10^{34} C_{35} \left(\frac{n_\chi}{100 \text{ GeV}}\right) \text{ erg s}^{-1},$$

where $C_{35}$ is the capture rate in units 10⁻³⁵ s⁻¹.
3. DISCUSSION AND CONCLUSION

Where does the energy released during the WIMP annihilation go? Table 1 shows that the typical radius of the thermal distribution of WIMPs in the star core $r_{th} \ll R_*$, therefore, the products of their annihilation cannot propagate to the star surface and are eventually converted into the thermal energy and neutrino emission. This may be not true for the white dwarfs whose radii are comparable to $r_{th}$, and where the effect of gravitational “focusing” is important (eqs. [8], second term in square brackets). While most of the energy is converted into heat, the surface of white dwarfs may emit products of WIMP annihilation, particles ($e^\pm, p, \bar{p}, \nu, \bar{\nu}$) and $\gamma$-rays, and this might be visible with a $\gamma$-ray telescope.

The WIMP capture rate generally increases with the star mass. However, the relative importance of WIMP annihilation diminishes in massive stars since their own luminosity increases as $\propto M^{3.5}$. Therefore, the interiors of massive stars will remain largely unaffected by WIMPs.

The WIMP burning affects mostly stars with $M \lesssim M_\odot$ with low to moderate luminosities and a large rate of WIMP capture. The typical luminosity of a sun-like star burning Hydrogen is $L_\odot = 3.8 \times 10^{33} \text{ erg s}^{-1}$, while WIMP annihilation in its core can provide up to $L_\chi \sim 4.6 \times 10^{33} \text{ erg s}^{-1}$, i.e. 10 times more. Such an additional energy source may exceed the star’s own resources from nuclear burning. The large concentration of WIMPs may also lead to more effective energy transport in the stellar core (Bouquet & Salati 1989) thus decreasing the core temperature and limiting the replenishment of the burning core with fresh nuclear fuel. Combined, these two effects could change the star’s evolution scenario, life expectancy, and appearance.

A white dwarf, a star without its own energy supply consisting of Carbon and Oxygen, may emit $L_\chi \sim 2 \times 10^{33} - 2 \times 10^{35} \text{ erg s}^{-1}$, i.e. 0.4–50 times luminosity of the sun, burning WIMPs only and this energy source will last forever! To reach such a luminosity, the surface temperature of the white dwarf should be in the range of $T \sim (80 - 150) \times 10^3 \text{ K}$ assuming $R = 0.01 R_\odot$. In comparison, the luminosity of a regular white dwarf does not exceed $\sim 0.01 L_\odot$. The interiors of white dwarfs are almost isothermal, and the energy transport is dominated by degenerate electrons (see Hansen 2004, for a recent review); therefore, the large number of captured WIMPs and their annihilation in the core would not change the structure of white dwarfs. Interestingly, since $L_\chi \propto \rho_\chi$, a population of such white dwarfs located at different distances from the central black hole will exhibit a luminosity correlated with the radial WIMP density distribution. A signature of a “dark matter burner” would be a very hot star with a mass and radius characteristic for a white dwarf, but with a luminosity exceeding the typical luminosity for a white dwarf by orders of magnitude $\lesssim 50 L_\odot$. Note that an independent determination of the $M_\star / R_*$ ratio is possible using the gravitational redshift which has to be equivalent to $v_R \sim 50 \text{ km s}^{-1}$ (Greenstein & Trimble 1967).

Furthermore, a low-mass star with a highly eccentric orbit around the central black hole may exhibit variations in brightness correlated with the orbital phase. The brightness should increase as the star approaches the periastron and some time after that. To have this working, the orbital period should essentially exceed $\tau_{eq}$. Carbon burning stars have $\tau_{eq} \sim 10\text{ yr}$. It is even shorter in case of a white dwarf $\tau_{eq} \sim 0.5\text{ yr}$. If a white dwarf appears in a high-density WIMP region, the WIMP density in its material quickly reaches equilibrium. On the other hand, the small radii of white dwarfs $R_\sim \sim 10 r_{th}$ imply that the captured WIMP density close to the surface may be large enough thus the surrounding WIMP density change will result in variations in their brightness. This makes white dwarfs ideal objects to test the WIMP density in the environment in which they are orbiting.

Advances in near-IR instrumentation have made possible the observation of stars in the inner parsec of the Galaxy (Genzel et al. 2000; Ghez et al. 2003, 2005). The observed absorption line widths imply high temperatures and lead to a “paradox of youth:” apparently young stars in the region whose current conditions seem to be inhospitable to star formation. One of the possibilities is that they are old stars masquerading as youths. If an independent determination of their mass reveals that some of them are low-mass stars, then they would become candidates for the dark matter burners.

The model predicts the existence of unusual stars and consequently unusual supernovae in the central parts of the galaxies. These are the stars burning WIMPs at a high rate whose luminosities essentially exceed the typical luminosity of a star of given mass. If found, such stars would be interesting probes of particle dark matter near supermassive black holes. Their luminosity, or rather their excess luminosity, attributed to the WIMP burning can be used to derive the WIMP matter density at their location. On the other hand, a lack of such unusual stars may provide constraints on WIMP density, WIMP-nucleus scattering and pair annihilation cross-sections.

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