

DARK MATTER BURNERS

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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. The excess luminosity of such stars attributed to WIMP “burning” can be used to infer the local WIMP matter density. A white dwarf with a highly eccentric orbit around the central black hole may exhibit variations in brightness correlated with the orbital phase. On the other hand, white dwarfs shown to lack such orbital brightness variations can be used to provide constraints on WIMP matter density, WIMP-nucleus scattering and pair annihilation cross sections.

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 γ -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.

We perform order-of-magnitude estimates of WIMP capture rates for stars in high density dark matter regions. The WIMP annihilation in such stars may lead to considerable energy release in the stellar cores thus affect-

ing the evolution scenario of such stars. More accurate calculations including the details of the stellar composition, density profile and so on, are therefore not warranted.

2. WIMP ACCUMULATION IN STARS

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

$$C = AN_{\chi}^2 \quad (1)$$

where N_{χ} is the total number of WIMPs in the star,

$$A = \langle \sigma_a v \rangle / V_{\text{eff}}, \quad (2)$$

$$V_{\text{eff}} = \pi^{3/2} r_{\chi}^3, \quad (3)$$

$\langle \sigma_a v \rangle$ is the velocity averaged WIMP pair annihilation cross-section, and the effective volume V_{eff} is determined by matching the core temperature T_c with the gravitational potential energy at the core radius r_{χ} (assuming thermal equilibrium). The total number of captured WIMPs is

$$N_{\chi} = C\tau_{eq} \tanh(\tau_{*}/\tau_{eq}), \quad (4)$$

where τ_{*} is the star age, and the equilibrium time scale is given by

$$\tau_{eq} = (CA)^{-1/2}. \quad (5)$$

The number density distribution of WIMPs can be estimated as (Press & Spergel 1985; Griest & Seckel 1987; Bottino et al. 2002):

$$n_{\chi}(r) = n_{\chi}^c \exp(-r^2/r_{\chi}^2), \quad (6)$$

where $n_{\chi}^c = N_{\chi}/V_{\text{eff}}$ is the central WIMP number density. In thermal equilibrium, the effective radius $r_{\chi} = r_T$ is determined by the core temperature T_c and density ρ_c

$$r_T = c \left(\frac{3T_c}{2\pi G \rho_c m_{\chi}} \right)^{1/2}, \quad (7)$$

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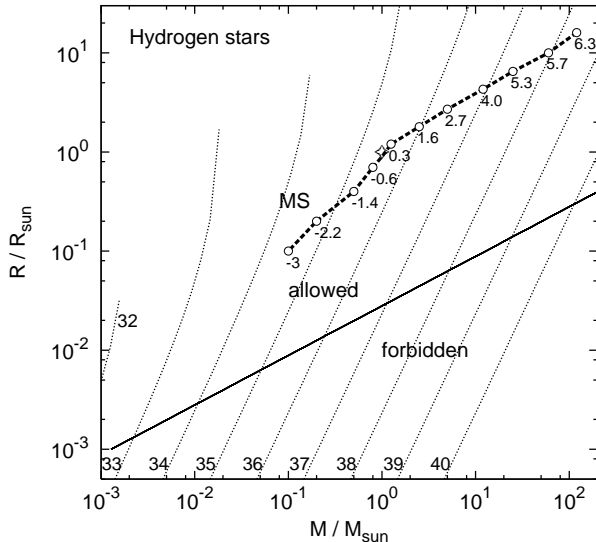


FIG. 1.— Mass-radius-capture rate diagram for Hydrogen stars. The dotted line series are calculated using eq. (9) and the numbers on the plot show the logarithm of WIMP capture rate $\log_{10} C$. The strong dashed line labeled “MS” shows characteristics of the main sequence stars (Massey & Meyer 2001), and the diamond symbol indicates a 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 $\log_{10}(L_*/L_{\odot})$. The solid line divides the diagram into “allowed” and “forbidden” parts, see text for more details.

where c is the speed of light, G is the gravitational constant, and m_{χ} 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 πR_*^2 , the WIMP velocity dispersion \bar{v} , and the ambient WIMP energy density ρ_{χ} :

$$C = \left(\frac{8}{3\pi}\right)^{1/2} \frac{\rho_{\chi}\bar{v}}{m_{\chi}} \left[\zeta + \frac{3v_{esc}^2}{2\bar{v}^2}\right] \pi R_*^2, \quad (8)$$

where ζ is taken to be 1.77, $v_{esc} = \sqrt{2GM_*/R_*}$ is the escape velocity at the star’s surface, and M_* is the star mass.

On the other hand, limits from direct detection of dark matter on the WIMP-nucleon cross-section imply that only a fraction of the WIMPs crossing the star will scatter and be captured. In this case the star’s cross-sectional area is replaced by the product of the WIMP-nucleon scattering cross-section σ_n , the number of nuclei, and a spin-independent coherent factor for nuclei heavier than Hydrogen, that is A_n^4 for a nucleus with the atomic mass A_n . The limits on spin-independent WIMP-nucleon scattering are more stringent than for spin-dependent; from direct detection experiments the spin-independent WIMP-nucleon scattering cross-section σ_0 is at most 10^{-43} cm^2 (CDMS 2006). The current limit on spin-dependent Hydrogen scattering comes from Super-Kamiokande, which finds that σ_s is at most 10^{-38} cm^2 (Super-Kamiokande 2004). In the following formulas we will use a generic cross-section σ_n to be substituted by σ_0 or σ_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

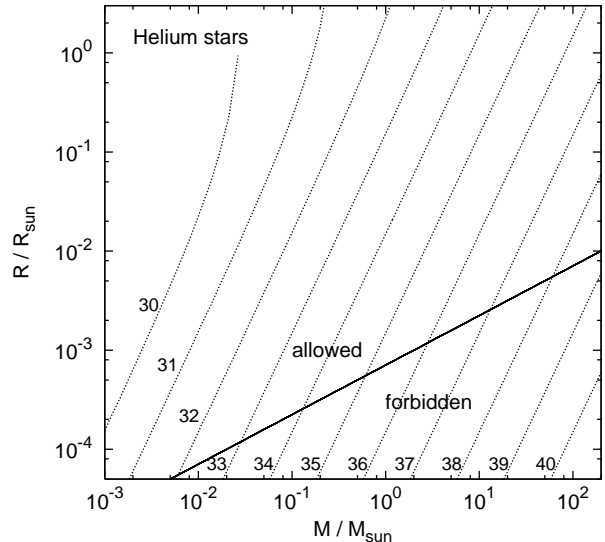


FIG. 2.— Mass-radius-capture rate diagram for Helium stars. Lines are coded as in Figure 1.

Hydrogen), we have for $m_{\chi} \gg A_n m_p$:

$$C = \left(\frac{8}{3\pi}\right)^{1/2} \frac{\rho_{\chi}\bar{v}}{m_{\chi}} \left[\zeta + \frac{3v_{esc}^2}{2\bar{v}^2}\right] \sigma_n A_n^4 \frac{M_*}{A_n m_p}, \quad (9)$$

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):

$$R_* \geq A_n^{3/2} \sqrt{\frac{\sigma_n M_*}{\pi m_p}}. \quad (10)$$

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 $\geq 35M_{\odot}$ and the solar metallicity to end their life as hydrogen-free objects of roughly $5M_{\odot}$; 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 $m_{\chi} = 100$ GeV, $\langle \sigma_a v \rangle = 3 \times 10^{-26}$ $\text{cm}^3 \text{s}^{-1}$, and WIMP velocity dispersion $\bar{v} = 270$ km s^{-1} . The value $\rho_{\chi} = 10^{10}$ GeV cm^{-3} corresponds to the maximal energy density allowed by the age of the supermassive black hole ~ 10 Gyr, and our selected values of $\langle \sigma_a v \rangle$ and m_{χ} (Gondolo & Silk 1999; Bertone & Merritt 2005). The spin-dependent and spin-independent WIMP-nucleon scattering cross sections are taken as $\sigma_s = 10^{-38}$ cm^2 and $\sigma_0 = 10^{-43}$ cm^2 , correspondingly. The series of dotted lines are calculated using eq. (9), and the numbers on the plots show the logarithm of WIMP capture rate $\log_{10} C$. The strong dashed

TABLE 1
WIMP ACCUMULATION DURING DIFFERENT BURNING STAGES

M_{init}^H	M_*	R_*	T_c	ρ_c	C	r_{th}	τ_{eq}	τ_*	N_χ	n_χ^c
M_\odot	M_\odot	R_\odot	10^8 K	g cm^{-3}	s^{-1}	10^8 cm	s	s		cm^{-3}
Hydrogen Stage										
1	1	1	0.157	153	2.85×10^{35}	7.55	5.29×10^8	3.47×10^{16}	1.51×10^{44}	6.30×10^{16}
13	12.9	6.24	0.344	6.66	6.88×10^{36}	53.5	2.04×10^9	4.26×10^{14}	1.40×10^{46}	1.64×10^{16}
25	24.5	9.17	0.381	3.81	1.65×10^{37}	74.5	2.16×10^9	2.11×10^{14}	3.56×10^{46}	1.55×10^{16}
75	67.3	21.3	0.426	1.99	5.30×10^{37}	109	2.13×10^9	9.97×10^{13}	1.13×10^{47}	1.56×10^{16}
75 ^a	75	9.36	0.760	10.6	1.44×10^{38}	63.1	5.69×10^8	1.09×10^{14}	8.19×10^{46}	5.85×10^{16}
Helium Stage										
1	0.71	10	1.25	20000	3.13×10^{31}	1.86	6.19×10^9	3.47×10^{15}	1.94×10^{41}	5.39×10^{15}
13	12.4	359	1.72	1730	4.80×10^{32}	7.43	1.26×10^{10}	8.43×10^{13}	6.05×10^{42}	2.65×10^{15}
25	19.6	1030	1.96	762	7.14×10^{32}	11.9	2.11×10^{10}	2.65×10^{13}	1.50×10^{43}	1.58×10^{15}
75	16.1	1.17	2.10	490	3.35×10^{34}	15.4	4.51×10^9	1.51×10^{13}	1.51×10^{44}	7.40×10^{15}
75 ^a	74.4	702	2.25	319	3.67×10^{33}	19.8	1.98×10^{10}	1.05×10^{13}	7.27×10^{43}	1.68×10^{15}
Carbon Stage										
~3	1.0	0.01	10	1.00×10^6	4.03×10^{35}	0.745	1.38×10^7	...	5.56×10^{42}	2.41×10^{18}
13	11.4	665	8.15	3.13×10^5	1.11×10^{34}	1.20	1.70×10^8	8.90×10^{10}	1.89×10^{42}	1.96×10^{17}
25	12.5	1390	8.41	1.29×10^5	1.18×10^{34}	1.90	3.29×10^8	1.65×10^{10}	3.88×10^{42}	1.01×10^{17}
75	6.37	0.644	8.68	1.39×10^5	2.59×10^{35}	1.86	6.80×10^7	3.38×10^{10}	1.76×10^{43}	4.90×10^{17}
75 ^a	74.0	714	10.4	7.45×10^4	9.79×10^{34}	2.78	2.02×10^8	8.52×10^8	1.98×10^{43}	1.65×10^{17}

NOTE. — M_{init}^H is the initial hydrogen star mass.

^aStellar model with 10^{-4} solar metallicity.

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 $\log_{10}(L_*/L_\odot)$. 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_* and R_* , 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 ($1 - 75M_\odot$) 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 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. The τ_* column shows the duration of the corresponding burning cycle.

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

$$L_\chi \sim 1.6 \times 10^{34} C_{35} \left[\frac{m_\chi}{100 \text{ GeV}} \right] \text{ erg s}^{-1}, \quad (11)$$

where C_{35} is the capture rate in units 10^{35} s^{-1} .

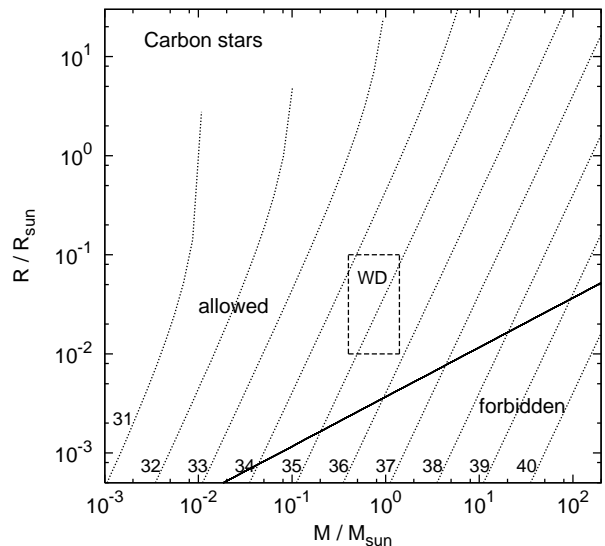


FIG. 3.— Mass-radius-capture rate diagram for Carbon stars. The rectangular area outlined by the dashed line and labeled “WD” shows parameter range typical for white dwarfs. Lines are coded as in Figure 1.

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 can not 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} . 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} , ν , $\bar{\nu}$) and γ -rays, and this might be visible with a γ -ray telescope.

The WIMP capture rate generally increases with the star mass. However, the relative importance of WIMP annihilation diminish in massive stars since their own luminosity increases as $\propto M_*^{3.5}$.

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 $L_\odot = 3.8 \times 10^{33}$ erg s $^{-1}$, while WIMP annihilation in its core can provide up to $L_\chi \sim 4.6 \times 10^{34}$ erg s $^{-1}$, i.e. 10 times more. Such an additional energy source exceeding the star's own resources should affect the star evolution. A white dwarf, a star without its own energy supply consisting of Carbon and Oxygen, may emit $L_\chi \sim 10^{34} - 10^{36}$ erg s $^{-1}$, i.e. 3–300 times luminosity of the sun, burning WIMPs only and this energy source will last forever! 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.

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 τ_{eq} . Carbon burning stars have $\tau_{eq} \sim 10$ yr. It is even shorter in case of a white dwarf $\tau_{eq} \sim 0.5$ yr. Regular white dwarfs do not have their own energy supply and can only cool down. 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 $R_* \sim 10r_{th}$ imply that the captured WIMP density close to the surface may be large enough thus the surrounding WIMP density change will result in varia-

tions in their brightness. This makes white dwarfs ideal objects to test the WIMP density in the environment in which they are orbiting.

The WIMP number density may increase during the sudden collapse of a massive star (Ullio et al. 2001). 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. If the WIMPs can be shown to form high enough density during the collapse of the massive star, then in principle the ‘‘burst’’ of annihilation radiation could be observable from cosmological distances. The energy release during sudden WIMP annihilation could also trigger a highly relativistic jet leading to a γ -ray burst event.

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. It does not seem possible to indicate more specific features of such stars in this paper since their evolution is affected by the relatively large amount of additional energy due to WIMP annihilation in the core.

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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