1 Introduction

2 Theories and models
   2.1 Dark matter capture by the stars
      2.1.1 Capture rate by hydrogen atoms
      2.1.2 Capture rate by heavier elements
   2.2 Dynamic of binary star systems

3 Effect of binary star parameters on CR of DM particles
   3.1 Effect of stellar masses (results and discussions)
   3.2 Effect of semi-major axis (results and discussions)
   3.3 Effect of eccentricity (results and discussions)

4 Discussion/Conclusion

5 Acknowledgments
Abstract

The distribution of dark matter (DM) inside galaxies is not uniform. Near the central regions, its density is the highest. Then, it is logical to suppose that, inside galaxies, DM affects the physics of stars in central regions more than outer regions. Besides, current stellar evolutionary models did not consider DM effects in their assumptions. To consider the DM effects, at first one must estimate how much DM a star contains. The capture rate (CR) of DM particles by individual stars was investigated already in the literature. In this work, we discuss how CR can be affected when stars are members of binary star systems (BSS) (instead of studying them individually). When a star is a member of a BSS, its speed changes periodically due to the elliptical motion around its companion star. In this work, we investigated CR by BSSs in different binary star system configurations. In the end, we discussed observational signatures that can be attributed to the DM effect in binary systems.

1 Introduction

According to the standard model of cosmology ($\Lambda$CDM model), about 25 percent of the matter in the universe is in the form of dark matter (DM). Besides, many other observational evidences support the existence of DM in large scales and small scales structures (e.g. rotation curves of galaxies, simulations of galaxies) in the universe. Rotation curves of galaxies show that DM distributed non-uniformly inside galaxies. Then, we can say, stars evolve inside galaxies while they are immersed in the DM. Therefore DM must affect the evolutionary course of stars inside galaxies.

Signs of DM effects on stars were investigated before this study in the literature. For example:

- For the first time Steigman used DM supposition on the sun to solve the discrepancy between the observed and calculated solar neutrino fluxes. Since then, many studies had conducted to solve the solar neutrino problem using the supposition that DM particles annihilate inside the sun.
- Simulation of dwarf galaxies, with the same mass, shows that the halo of DM around evolved dwarf galaxies can be heated-up by star formation process inside galaxies and then push the DM around. The more evolved the dwarf galaxy is then, the more DM halo heated-up by stars.
- Stars that evolve near the Galactic massive blackhole show signs of young and old stars simultaneously, which is known as the paradox of youth problem. Supposing that DM particles annihilate inside stars can solve this problem.
- In addition to the normal stars, the effects of DM on compact stars (white dwarfs and neutron stars) were also investigated in the literature. For instance, the annihilation of DM particles inside compact stars can flatter out their temperature or it is possible to constrain DM properties using compact stars.

According to the definition, capture rate (CR) of DM particles by an around massive body (like Earth, Sun, neutron stars, etc) is the number of DM particles that are gravitationally bound to that body by passing the time. For the first time, Press and Spergel calculated CR of Weakly interacting massive particles (WIMP) by the sun. Then, Gould generalized the CR relation for other round objects (like planets and stars). Since then, many other studies used...
Gould relation to calculate CR by massive round bodies\cite{15,16}. In this study, we used Gould relation to calculate CR by stars (see section 2.1 for more details).

Accumulation of DM particles inside massive bodies (whether they annihilate or they do not) can alter the structure and evolutionary course of stars\cite{19,20}. Therefore, they can be responsible for some observational phenomenon like gamma ray\cite{21,22} and neutrino emission from stars\cite{23}. This effect is boosted for stars that are located in high DM density environments e.g. near the Galactic massive black hole (as they can capture more WIMP in units of time). Then, it is important to estimate the CR value by massive bodies as much as possible. CR for different kind of round massive bodies like the Moon\cite{28,33}, planets (like Earth and exoplanets),\cite{25,34,35} the Sun,\cite{23,37,38} other stars,\cite{6,7,39,40,41,42} compact stars,\cite{12,13,44,45} are estimated in the literature.

To the best of our knowledge, the effects of DM on compact binary systems were investigated in the literature\cite{46,47,48,49}. But we could not find a similar topic for normal (non-compact) binary systems. So, in this study, we estimated the CR by BSSs and then discussed the effects of binary parameters on CR. Section 2 is devoted to the theories and models that are used in this work. The formulas that are used in this study, was derived in this section too. In section 3, the effects of binary system parameters on CR were investigated. Finally, section 4 is devoted to conclusions and discussions. Possible observational signs of DM effects in binary systems are discussed in this section too.

2 Theories and models

2.1 Dark matter capture by the stars

We used Gould relations to calculate CR by stars\cite{17}. The total CR by different elements inside stars can be calculated using the Gould relation\cite{1}:

\[
C_\chi(t) = \sum_i \int_0^{R_\ast} 4\pi r^2 \int_0^\infty f_{v,i}(u) u \Omega_{v,i}(\omega) dudr.
\] (1)

In sections 2.1.1 and 2.1.2 we calculated CR relation for hydrogen and heavier elements separately. In equation 1, \(\Omega_{v,i}^{-}\) is the rate at which a WIMP with velocity \(\omega\) scatters to a velocity less than \(v\) (escape velocity from the surface of the star) and then gravitationally bounds. For hydrogen atoms \(\Omega_{v,H}^{-}\) is:

\[
\Omega_{v,H}^{-}(\omega) = \frac{\sigma_{\chi,H} n_H(r)}{\omega} (v_e^2 - \frac{\mu_H^2}{\mu_H^2} u^2) \theta (v_e^2 - \frac{\mu_H^2}{\mu_H^2} u^2)
\] (2)

where \(\theta\) is the step function. For heavier elements \(\Omega_{v,i}^{-}\) is:

\[
\Omega_{v,i}^{-}(\omega) = \frac{\sigma_{\chi,i} n_i(r)}{\omega} \frac{2E_0 \mu_{i,i}^2}{m_\chi \mu_i} \left\{ \exp(-\frac{m_\chi u_e^2}{2E_0}) - \exp(-\frac{m_\chi u_e^2}{2E_0} \frac{\mu_i}{\mu_{i,i}}) \exp(-\frac{m_\chi v_e^2}{2E_0} \frac{1 - \mu_i}{\mu_{i,i}^2}) \right\}
\] (3)

\(^1\)Recently, a more generalized form of CR was suggested in the paper\cite{50}, which authors considered the arbitrary mass mediators in the CR relation. But, for the purposes of this paper, there is not a significant difference between the Gould relation and the relation in the paper\cite{50}.
in which \( E_0 \) is the characteristic coherence energy and can be calculated using (see reference 13 for more details):

\[
E_0 = \frac{3\hbar^2}{2m_{n,i}(0.91m_{n,i}^{1/3} + 0.3)^2}
\]  

(4)

In equation 1 we have:

\[
\mu_{\mp,i} = \frac{\mu_i \pm 1}{2}
\]

(5)

and

\[
\mu_i = \frac{m_chi}{m_{n,i}}
\]

(6)

\( f_v(u) \) is the velocity distribution function of DM particles at the location of the star. \( f_v(u) \) usually considered a Maxwell-Boltzmann distribution with a dispersion velocity \( \sigmachi \):

\[
f_v(u) = f_0(u) \exp\left(-\frac{3u^2}{2\sigmachi^2}\right)
\]

(7)

in which \( f_0(u) \) is the velocity dispersion of the DM particles in the halo and is:

\[
f_0(u) = \frac{\rhochi}{mchi \sqrt{\pi}} \left(\frac{3}{2}\right)^{3/2} \frac{u^2}{\sigmachi^2} \exp\left(-\frac{3u^2}{2\sigmachi^2}\right)
\]

(8)

\( \sigmachi,i \) is the scattering cross section from an element \( i \). For hydrogen atoms, \( \sigmachi,i \) is:

\[
\sigmachi,H = \sigmachi,SI + \sigmachi,SD
\]

(9)

and for elements heavier than hydrogen it is:

\[
\sigmachi,i = \sigmachi,SI A_i^2 \left(\frac{mchi m_{n,i}}{mchi + m_{n,i}}\right)^2 \left(\frac{mchi + mp}{mchi mp}\right)^2
\]

(10)

In above equations \( \sigmachi,SI \) is the spin-independent DM-nucleon scattering cross section, \( \sigmachi,SD \) is the spin-dependent DM-nucleon scattering cross section, \( mchi \) is the mass of the DM particles (WIMPs, in the case of this study), \( m_{n,i} \) is the nuclear mass of the element \( i \), \( A_i \) is the atomic number of the element \( i \), \( n_i(r) \) is the number density of the element \( i \) at a radius \( r \) from the center of the star, and \( R_* \) is the radius of the star.

In the coming two sections, we will calculate CR relation for hydrogen and heavier elements separately.

2.1.1 Capture rate by hydrogen atoms

After putting equations 2, 7, 8 and 9 into equation 11 and then some arrangements, we obtain the CR relation for hydrogen atoms:

\[
C_{chi,H} = \left[4\sqrt{\frac{6\pi}{mchi vchi}} \frac{1}{vchi u_H} \exp\left(-\frac{3u_H^2}{2vchi}\right)\right] [\sigmachi,SI + \sigmachi,SD] \left[ \int_0^{R_*} n_H(r)r^2dr\right]
\]

\[
\left[ \int_0^\infty \exp\left(-\frac{3u^2}{2vchi}\right) \sinh\left(\frac{3uH}{vchi}\right)(v^2 - \frac{u^2}{\mu_H})\theta(v^2 - \frac{u^2}{\mu_H})du \right]
\]

(11)
2.1.2 Capture rate by heavier elements

After putting equations 3, 7, 8 and 10 into equation 1 and then some arrangements, we obtain the capture rate for heavier elements:

\[
C_{\chi,H} = \left[ 8\sqrt{6\pi} \frac{m_{\chi} E_0}{v_{\chi} v_*} \exp\left( -\frac{3v_*^2}{2m_{\chi}} \right) \right] \left[ \sigma_{\chi,SI} A_i^2 \left( \frac{m_{\chi} m_{n,i}}{m_{\chi} + m_{n,i}} \right)^2 \left( \frac{m_{\chi} + m_p}{m_{\chi} m_p} \right)^2 \right] \int_{0}^{R_*} n_H(r)r^2 dr \\
\int_{0}^{\infty} \exp\left( -\frac{3v_*^2}{2m_{\chi}} \right) \sinh\left( \frac{3v_*^2}{2m_{\chi}} \right) \left\{ \exp\left( -\frac{m_{\chi} u^2}{2E_0} \right) - \exp\left( -\frac{m_{\chi} u^2}{2E_0} \frac{\mu_i}{\mu_{+,i}} \right) \exp\left( -\frac{m_{\chi} u^2}{2E_0} \frac{\mu_i}{\mu_{-,i}} \left( 1 - \frac{\mu_i}{\mu_{+,i}} \right) \right) \right\} \right] 
\]

(12)

Though it seems impossible to evaluate equations 11 and 12 analytically, but it is possible to evaluate them using the state of the art stellar evolutionary codes. In this study, we used version 12778 of MESA stellar evolutionary code to calculate CR by stars. MESA is a free and open-source stellar evolutionary code that can simulate stars from very low-mass ones to the very high-mass ones (\( \approx 10^{-3} - 10^3 M_\odot \)). The full capabilities of MESA are documented in its official instrument papers.

2.2 Dynamic of binary star systems

According to the equations 11 and 12, CR by stars is a function of the speed of the stars \( v_* \). Then, CR by each star within the BSS will change while stars orbit around each other in an elliptical motion. In this section, we review the necessary equations that are needed to describe the motion of stars in BSSs.

If two stars with masses \( M_1 \) and \( M_2 \) orbit around each other in an elliptical motion with semi-major axis \( a \) and ellipticity \( e \), then the orbital period of the system can be evaluated:

\[
P^2 = \frac{4\pi^2 a^3}{GM} \tag{13}
\]

where \( M = M_1 + M_2 \). Speed of stars in periastron and apastron can be calculated using:

\[
V_p = \sqrt{\frac{GM(1+e)}{a(1-e)}} \tag{14}
\]

and

\[
V_a = \sqrt{\frac{GM(1-e)}{a(1+e)}} \tag{15}
\]

3 Effect of binary star parameters on CR of DM particles

In this section, we investigated BSSs parameter effects on the CR of DM particles. In binary systems, the speed of the stars is not constant as they usually follow elliptical motion rather than circular. This speed variation causes the periodic changes in the CR by each star and also periodic changes in the total CR by the system. During the research, we calculated CR by stars when they are in the zero-age main-sequence phase (ZAMS). Also, we supposed that binary components have consisted of a combination of a low-mass star (1.0 \( M_\odot \)), an intermediate-mass star (5.0 \( M_\odot \)) and
a high-mass star (50.0 $M_{\odot}$). DM density around stars supposed to be $1000 \text{ Gev c}^{-2}\text{cm}^{-3}$ and consisted of WIMPs with masses $100 \text{ Gev c}^{-2}$.

3.1 Effect of stellar masses (results and discussions)

Using MESA stellar evolutionary code, CR by binary systems with different stellar masses are calculated and then summarized in the table 1. In table 1, the eccentricity of all systems considered to be $e = 0.9$ and semi-major axes to be $a = 10 \text{ AU}$. The overall result are:

- When stars are in apastron, they captures more DM particles in comparison to the time when they are in periastron (for instance compare $T_1$ and $T_4$ or $T_2$ and $T_3$ in table 1). This is because, when stars aproches to the apastron, their speed reduces and then, according to the equations 11 and 12, CR by stars increases.

- In our simulations, the most striking CR variation occurs for systems that the total mass of the system ($M_1 + M_2$) is the highest. In system (4) (in table 1) with the lowest total mass $M_1 + M_2 = 2.0 \, M_{\odot}$ the CR variation is:

  \[
  \text{for } 1.0 \, M_{\odot} \text{ star: } \frac{T_{14} - T_{13}}{T_{13}} \times 100 \simeq 7.12 \%.
  \] (16)

  For system (3) with increased total mass $M_1 + M_2 = 6.0 \, M_{\odot}$, the CR variation increases to:

  \[
  \text{for } 1.0 \, M_{\odot} \text{ star: } \frac{T_{12} - T_9}{T_9} \times 100 \simeq 22.96 \% \\
  \text{for } 5.0 \, M_{\odot} \text{ star: } \frac{T_{10} - T_{11}}{T_{10}} \times 100 \simeq 23.08 \%.
  \] (17)

  In system (5) with increased total mass $M_1 + M_2 = 10.0 \, M_{\odot}$, the CR variation increases to:

  \[
  \text{for } 5.0 \, M_{\odot} \text{ star: } \frac{T_{16} - T_{15}}{T_{15}} \times 100 \simeq 40.8 \%.
  \] (18)

  In system (1) with increased total mass $M_1 + M_2 = 51.0 \, M_{\odot}$, the CR variation increases to:

  \[
  \text{for } 1.0 \, M_{\odot} \text{ star: } \frac{T_4 - T_1}{T_1} \times 100 \simeq 484.96 \% \\
  \text{for } 50.0 \, M_{\odot} \text{ star: } \frac{T_2 - T_3}{T_2} \times 100 \simeq 465.53 \%.
  \] (19)

  In system (2) with increased total mass $M_1 + M_2 = 55.0 \, M_{\odot}$ the CR variation increases to:

  \[
  \text{for } 5.0 \, M_{\odot} \text{ star: } \frac{T_8 - T_5}{T_5} \times 100 \simeq 562.87 \% \\
  \text{for } 50.0 \, M_{\odot} \text{ star: } \frac{T_6 - T_7}{T_6} \times 100 \simeq 548.12 \%.
  \] (20)

  And in system (6) with the highest total mass $M_1 + M_2 = 100.0 \, M_{\odot}$ the CR variation is the highest:

  \[
  \text{for } 50.0 \, M_{\odot} \text{ star: } \frac{T_{18} - T_{17}}{T_{17}} \times 100 \simeq 2893.55 \%.
  \] (21)

  This behaviour can be inferred by subtraction of the equations 14 and 15 which leads to:

  \[
  v_p - v_a = \sqrt{\frac{GM}{a}} \left[ \sqrt{\frac{1 + e}{1 - e}} - \sqrt{\frac{1 - e}{1 + e}} \right].
  \] (22)

  Then, one can say, the bigger the M is, then the bigger the speed subtraction $v_p - v_a$ is. Then, according to the equations 11 and 12, the bigger the $v_p - v_a$ is, then the bigger the CR variation is.
Table 1: CR in BSSs with unequall and equall (last 3 rows) stellar mass components.

| $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $v_{1,p}$ (m/sec$^{-1}$) | $v_{2,a}$ (m/sec$^{-1}$) | $CR$ by $M_1$ (sec$^{-1}$) | $CR$ by $M_2$ (sec$^{-1}$) | $CR_M$ (sec$^{-1}$) | system number |
|-------------------|-------------------|-------------------------|-------------------------|------------------------|------------------------|----------------------|---------------|
| 1.0               | 50.0              | 293558                  | 15450                   | $T_1 = 6.65 \times 10^{22}$ | $T_2 = 4.66 \times 10^{27}$ | $T_{1+2} = 4.66 \times 10^{27}$ | system (1) |
| 50.0              | 1.0               | 293558                  | 15450                   | $T_3 = 8.24 \times 10^{26}$ | $T_4 = 3.89 \times 10^{23}$ | $T_{3+4} = 8.24 \times 10^{26}$ |               |
| 5.0               | 50.0              | 304853                  | 16045                   | $T_5 = 2.64 \times 10^{25}$ | $T_6 = 4.66 \times 10^{27}$ | $T_{5+6} = 4.69 \times 10^{27}$ | system (2) |
| 50.0              | 5.0               | 304853                  | 16045                   | $T_7 = 7.19 \times 10^{26}$ | $T_8 = 1.75 \times 10^{23}$ | $T_{7+8} = 8.94 \times 10^{26}$ |               |
| 1.0               | 5.0               | 100690                  | 5299                    | $T_9 = 3.18 \times 10^{23}$ | $T_{10} = 1.76 \times 10^{26}$ | $T_{9+10} = 1.76 \times 10^{26}$ | system (3) |
| 5.0               | 1.0               | 100690                  | 5299                    | $T_{11} = 1.43 \times 10^{26}$ | $T_{12} = 3.91 \times 10^{23}$ | $T_{11+12} = 1.43 \times 10^{26}$ |               |
| 1.0               | 1.0               | 58133                   | 3060                    | $T_{13} = 3.65 \times 10^{23}$ | $T_{14} = 3.91 \times 10^{23}$ | $T_{13+14} = 7.56 \times 10^{23}$ | system (4) |
| 5.0               | 5.0               | 129990                  | 6842                    | $T_{15} = 1.25 \times 10^{26}$ | $T_{16} = 1.76 \times 10^{26}$ | $T_{15+16} = 3.01 \times 10^{26}$ | system (5) |
| 50.0              | 50.0              | 411064                  | 21635                   | $T_{17} = 1.55 \times 10^{26}$ | $T_{18} = 4.64 \times 10^{27}$ | $T_{17+18} = 4.79 \times 10^{27}$ | system (6) |

* Speed of $M_1$ star when it is in periastron.
** Speed of $M_2$ star when it is in apastron.
*** $CR$ by $M_1$ star when it is in periastron and when it is in ZAMS phase.
**** $CR$ by $M_2$ star when it is in apastron and when it is in ZAMS phase.
***** Total $CR : CR_M = CR_{M1} + CR_{M2}$

3.2 Effect of semi-major axis (results and discussions)

In order to study the effect of semi-major axis on the CR by BSSs, we keep all parameters of the systems to be constant, except the semi-major axis. The results of the simulations are presented in table 2 for binaries with equal component masses and in table 3 for binaries with unequal component masses. In all system, the eccentricities of the systems considered to be constant : $e = 0.9$. The overall results that can be inferred from the tables 2 and 3 are:

- CR by the 50 $M_\odot$ star in the system (15) in the table 2 is negative, i.e. $T_{35} = -1.8638 \times 10^{13}$. This means, the star loses DM particles instead of capturing them. The reason for being negative in this case is the very high speed of the 50 $M_\odot$ star. Its speed at the periastron is $v_\star = 1299897 \text{ m sec}^{-1}$ (this speed is not presented in the table 2). While the escape velocity at the surface of the 50 $M_\odot$ star when it is at ZAMS phase is $v_{\text{escape}} = 273904 \text{ m sec}^{-1}$ (we used MESA stellar evolutionary code to obtain the escape velocity of the stars). As a result, we can say, in close binary systems, CR by stars can be negative.

- According to the results of our simulations that are presented in tables 2 and 3 by increasing the semi-major axis, the total CR by the binary systems will increase. This result can be inferred from analytical relations too. According to the equations 14 and 15 by increasing the semi-major axis “a” the amounts of $v_p$ and $v_a$ will decrease. Then, according to equations 11 and 12 by decreasing stars velocities the CR by stars will increase.

3.3 Effect of eccentricity (results and discussions)

In order to study the effect of eccentricity on the CR by BSSs, we keep all parameters of the binary systems to be constant, except the eccentricity. The results of our simulations are presented in table 4 for binaries with equal...
component masses and in table 5 for binaries with unequal component masses. In all systems, the semi-major axes considered to be constant: $a = 10 \, \text{AU}$. The overall results that can be inferred from the tables 4 and 5 are:

- According to the total CR amounts in table 4 in BSSs with equal stellar-mass components, by increasing the eccentricity of a system, the total CR decreases. This result is not correct for binaries with unequal stellar-mass components (e.g. see the total CR results in table 5).

- According to the CR amounts in tables 4 and 5 the most dramatic CR variations happen in the binaries with the highest eccentricities. For instance, in table 4 for 1.0 $M_\odot - 1.0 \, M_\odot$ binary system, the CR variations for different eccentricity configurations are (for systems (43)-(46)):

$$T_{92} - T_{91} = 0 \quad (23)$$

$$T_{94} - T_{93} = 1.88 \times 10^{21} \quad (24)$$

$$T_{96} - T_{95} = 5.32 \times 10^{21} \quad (25)$$

$$T_{98} - T_{97} = 2.618 \times 10^{22} \quad (26)$$

The similar trend happens to 5.0 $M_\odot - 5.0 \, M_\odot$ and 50.0 $M_\odot - 50.0 \, M_\odot$ binary systems. As an example, for binaries with different stellar-mass components, consider the 1.0 $M_\odot - 50.0 \, M_\odot$ binary systems in table 5 (systems (55)-(58)). CR variation in these systems are:

$$T_{116} - T_{115} = 4.2777 \times 10^{27} \quad (27)$$

| $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $a$ (AU) | $CR_{M1}$ ($sec^{-1}$) | $CR_{M2}$ ($sec^{-1}$) | $CR_M$ ($sec^{-1}$) | Number |
|-------------------|-------------------|----------|-------------------------|-------------------------|----------------------|--------|
| 1.0               | 1.0               | 1        | $T_{19} = 1.9534 \times 10^{23}$ | $T_{20} = 3.9055 \times 10^{23}$ | $T_{19+20} = 5.86 \times 10^{23}$ | system (7) |
|                   |                   | 10       | $T_{21} = 3.6504 \times 10^{23}$ | $T_{22} = 3.9122 \times 10^{23}$ | $T_{21+22} = 7.56 \times 10^{23}$ | system (8) |
|                   |                   | 100      | $T_{23} = 3.8859 \times 10^{23}$ | $T_{24} = 3.9129 \times 10^{23}$ | $T_{23+24} = 7.80 \times 10^{23}$ | system (9) |
|                   |                   | 1000     | $T_{25} = 3.9103 \times 10^{23}$ | $T_{26} = 3.9130 \times 10^{23}$ | $T_{25+26} = 7.82 \times 10^{23}$ | system (10) |
| 5.0               | 5.0               | 1        | $T_{27} = 5.5871 \times 10^{24}$ | $T_{28} = 1.7445 \times 10^{25}$ | $T_{27+28} = 1.80 \times 10^{26}$ | system (11) |
|                   |                   | 10       | $T_{29} = 1.2474 \times 10^{26}$ | $T_{30} = 1.7596 \times 10^{26}$ | $T_{29+30} = 3.01 \times 10^{26}$ | system (12) |
|                   |                   | 100      | $T_{31} = 1.7015 \times 10^{26}$ | $T_{32} = 1.7611 \times 10^{26}$ | $T_{31+32} = 3.46 \times 10^{26}$ | system (13) |
|                   |                   | 1000     | $T_{33} = 1.7552 \times 10^{26}$ | $T_{34} = 1.7613 \times 10^{26}$ | $T_{33+34} = 3.52 \times 10^{26}$ | system (14) |
| 50.0              | 50.0              | 1        | $T_{35} = -1.8638 \times 10^{13}$ | $T_{36} = 4.2655 \times 10^{27}$ | $T_{35+36} = 4.2655 \times 10^{26}$ | system (15) |
|                   |                   | 10       | $T_{37} = 4.6438 \times 10^{27}$ | $T_{38} = 1.5534 \times 10^{26}$ | $T_{37+38} = 4.6593 \times 10^{27}$ | system (16) |
|                   |                   | 100      | $T_{39} = 3.3338 \times 10^{27}$ | $T_{40} = 4.6834 \times 10^{27}$ | $T_{39+40} = 8.0172 \times 10^{27}$ | system (17) |
|                   |                   | 1000     | $T_{41} = 4.5307 \times 10^{27}$ | $T_{42} = 4.6874 \times 10^{27}$ | $T_{41+42} = 9.2181 \times 10^{27}$ | system (18) |

* Semi-major axis in astronomical unit (AU)

** CR by $M_1$ star when it is in periastron and when it is in ZAMS phase.

*** CR by $M_2$ star when it is in apastron and when it is in ZAMS phase.

**** Total CR: $CR_M = CR_{M1} + CR_{M2}$
Table 3: CR in BSSs with unequal stellar-mass components and different semi-major axes configurations.

| $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $a$ (AU) | $CR_{M1}$ $(sec^{-1})$ | $CR_{M2}$ $(sec^{-1})$ | $CR_M$ $(sec^{-1})$ | system number |
|-------------------|-------------------|---------|--------------------------|--------------------------|--------------------------|---------------|
| 1.0               | 50.0              | 1       | T_{43} = 7.8872 x 10^{25} | T_{44} = 4.4674 x 10^{27} | T_{43+44} = 4.4674 x 10^{27} | system (19)   |
|                   |                   | 10      | T_{45} = 6.6544 x 10^{22} | T_{46} = 4.6653 x 10^{27} | T_{45+46} = 4.6654 x 10^{27} | system (20)   |
|                   |                   | 100     | T_{47} = 3.2777 x 10^{23} | T_{48} = 4.6856 x 10^{27} | T_{47+48} = 4.6859 x 10^{27} | system (21)   |
|                   |                   | 1000    | T_{49} = 3.8443 x 10^{23} | T_{50} = 4.6876 x 10^{27} | T_{49+50} = 4.6880 x 10^{27} | system (22)   |
| 50.0              | 1.0               | 1       | T_{51} = 1.3027 x 10^{20} | T_{52} = 3.7256 x 10^{23} | T_{51+52} = 3.7269 x 10^{23} | system (23)   |
|                   |                   | 10      | T_{53} = 8.2445 x 10^{26} | T_{54} = 3.8938 x 10^{23} | T_{53+54} = 8.2484 x 10^{26} | system (24)   |
|                   |                   | 100     | T_{55} = 3.9398 x 10^{27} | T_{56} = 3.9111 x 10^{23} | T_{55+56} = 3.9402 x 10^{27} | system (25)   |
|                   |                   | 1000    | T_{57} = 4.6071 x 10^{27} | T_{58} = 3.9128 x 10^{23} | T_{57+58} = 4.6075 x 10^{27} | system (26)   |
| 5.0               | 50.0              | 1       | T_{59} = 8.7576 x 10^{17} | T_{60} = 4.4506 x 10^{27} | T_{59+60} = 4.4506 x 10^{27} | system (27)   |
|                   |                   | 10      | T_{61} = 2.6406 x 10^{25} | T_{62} = 4.6636 x 10^{27} | T_{61+62} = 4.6900 x 10^{27} | system (28)   |
|                   |                   | 100     | T_{63} = 1.4569 x 10^{26} | T_{64} = 4.6854 x 10^{27} | T_{63+64} = 4.8311 x 10^{27} | system (29)   |
|                   |                   | 1000    | T_{65} = 1.7282 x 10^{26} | T_{66} = 4.6876 x 10^{27} | T_{65+66} = 4.8604 x 10^{27} | system (30)   |
| 50.0              | 5.0               | 1       | T_{67} = 3.2578 x 10^{19} | T_{68} = 1.6711 x 10^{26} | T_{67+68} = 1.6711 x 10^{26} | system (31)   |
|                   |                   | 10      | T_{69} = 7.1941 x 10^{26} | T_{70} = 1.7520 x 10^{26} | T_{69+70} = 8.9461 x 10^{26} | system (32)   |
|                   |                   | 100     | T_{71} = 3.8865 x 10^{27} | T_{72} = 1.7603 x 10^{26} | T_{71+72} = 4.0625 x 10^{27} | system (33)   |
|                   |                   | 1000    | T_{73} = 4.6008 x 10^{27} | T_{74} = 1.7612 x 10^{26} | T_{73+74} = 4.7769 x 10^{27} | system (34)   |
| 1.0               | 5.0               | 1       | T_{75} = 4.8678 x 10^{22} | T_{76} = 1.7512 x 10^{26} | T_{75+76} = 1.7517 x 10^{26} | system (35)   |
|                   |                   | 10      | T_{77} = 3.1768 x 10^{23} | T_{78} = 1.7603 x 10^{26} | T_{77+78} = 1.7635 x 10^{26} | system (36)   |
|                   |                   | 100     | T_{79} = 3.8323 x 10^{23} | T_{80} = 1.7612 x 10^{26} | T_{79+80} = 1.7650 x 10^{26} | system (37)   |
|                   |                   | 1000    | T_{81} = 3.9048 x 10^{23} | T_{82} = 1.7613 x 10^{26} | T_{81+82} = 1.7652 x 10^{26} | system (38)   |
| 5.0               | 1.0               | 1       | T_{83} = 4.8678 x 10^{22} | T_{84} = 1.7512 x 10^{26} | T_{83+84} = 1.7517 x 10^{26} | system (39)   |
|                   |                   | 10      | T_{85} = 3.1768 x 10^{23} | T_{86} = 1.7603 x 10^{26} | T_{85+86} = 1.7635 x 10^{26} | system (40)   |
|                   |                   | 100     | T_{87} = 3.8323 x 10^{23} | T_{88} = 1.7612 x 10^{26} | T_{87+88} = 1.7650 x 10^{26} | system (41)   |
|                   |                   | 1000    | T_{89} = 3.9048 x 10^{23} | T_{90} = 1.7613 x 10^{26} | T_{89+90} = 1.7652 x 10^{26} | system (42)   |

* Semi-major axis in astronomical unit (AU)

** CR by $M_1$ star when it is in periastron and when it is in ZAMS phase.

*** CR by $M_2$ star when it is in apastron and when it is in ZAMS phase.

**** Total CR : $CR_M = CR_{M1} + CR_{M2}$
Table 4: CR in BSSs with equall stellar-mass components and different eccentricities.

| $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $e^*$ | $CR_{M1}^{**}$ (sec$^{-1}$) | $CR_{M2}^{**}$ (sec$^{-1}$) | $CR_M^{***}$ (sec$^{-1}$) | system number |
|-------------------|-------------------|------|----------------------------|----------------------------|---------------------------|---------------|
| 1.0               | 1.0               | 0 (circle) | $T_{91} = 3.8987 \times 10^{23}$ | $T_{92} = 3.8987 \times 10^{23}$ | $T_{94} = 3.9053 \times 10^{23}$ | system (43) |
|                   |                   | 0.3   | $T_{93} = 3.8865 \times 10^{23}$ | $T_{94} = 3.9053 \times 10^{23}$ | $T_{96} = 3.9094 \times 10^{23}$ | system (44) |
|                   |                   | 0.6   | $T_{95} = 3.8562 \times 10^{23}$ | $T_{96} = 3.9094 \times 10^{23}$ | $T_{98} = 3.9122 \times 10^{23}$ | system (45) |
|                   |                   | 0.9   | $T_{97} = 3.6504 \times 10^{23}$ | $T_{98} = 3.9122 \times 10^{23}$ | $T_{97+98} = 7.5626 \times 10^{23}$ | system (46) |
| 5.0               | 5.0               | 0 (circle) | $T_{99} = 1.7296 \times 10^{26}$ | $T_{100} = 1.7296 \times 10^{26}$ | $T_{99+100} = 3.4592 \times 10^{26}$ | system (47) |
|                   |                   | 0.3   | $T_{101} = 1.7029 \times 10^{26}$ | $T_{102} = 1.7441 \times 10^{26}$ | $T_{101+102} = 3.4470 \times 10^{26}$ | system (48) |
|                   |                   | 0.6   | $T_{103} = 1.6379 \times 10^{26}$ | $T_{104} = 1.7533 \times 10^{26}$ | $T_{103+104} = 3.3912 \times 10^{26}$ | system (49) |
|                   |                   | 0.9   | $T_{105} = 1.2474 \times 10^{26}$ | $T_{106} = 1.7596 \times 10^{26}$ | $T_{105+106} = 3.0070 \times 10^{26}$ | system (50) |
| 50.0              | 50.0              | 0 (circle) | $T_{107} = 3.9180 \times 10^{27}$ | $T_{108} = 3.9180 \times 10^{27}$ | $T_{107+108} = 7.8360 \times 10^{27}$ | system (51) |
|                   |                   | 0.3   | $T_{109} = 3.3596 \times 10^{27}$ | $T_{110} = 4.2562 \times 10^{27}$ | $T_{109+110} = 7.6158 \times 10^{27}$ | system (52) |
|                   |                   | 0.6   | $T_{111} = 2.2874 \times 10^{27}$ | $T_{112} = 4.4822 \times 10^{27}$ | $T_{111+112} = 6.7696 \times 10^{27}$ | system (53) |
|                   |                   | 0.9   | $T_{113} = 1.5534 \times 10^{26}$ | $T_{114} = 4.6438 \times 10^{27}$ | $T_{113+114} = 4.7991 \times 10^{27}$ | system (54) |

* Eccentricity.

** CR by $M_1$ star when it is in periastron and when it is in ZAMS phase.

*** CR by $M_2$ star when it is in apastron and when it is in ZAMS phase.

**** Total CR : $CR_M = CR_{M1} + CR_{M2}$

\[
\text{for system (56)} : \quad T_{118} - T_{117} = 4.4622 \times 10^{27} \quad (28)
\]

\[
\text{for system (57)} : \quad T_{120} - T_{119} = 4.5815 \times 10^{27} \quad (29)
\]

\[
\text{for system (58)} : \quad T_{122} - T_{121} = 4.6646 \times 10^{27}. \quad (30)
\]

The similar behaviour happens to other systems in table 5 too. As a result, CR variation boosted when stars follow elliptical rather than circular orbits.

4 Discussion/Conclusion

CR of DM particles in BSSs is discussed. At first, we presented the necessary equations that are needed to calculate CR by binary star systems in section 2. Equations 11 and 12 are the equations that we used in MESA stellar evolutionary code to calculate CR. Equations 11 and 12 are functions of stars relative velocity ($v_{\ast}$) with respect to the DM halo in the galaxy. Then, by changing stars velocity during the elliptical motion, the amount of CR by each star within the binary system changes too. In section 3, effect of different BSS parameters on CR were investigated. The overall results are:

- CR can be negative in some configurations. It means stars lose DM instead of capturing them. This happens in stars that their relative velocity (with respect to the DM halo) is higher than their escape velocity from the surface: $v_{\ast} > v_{\text{esca}}$ (see section 4.2 for more details).

- When stars are in apastron, they capture more DM particles in comparison to the time when they are in periastron (see section 5.1 for more details).
Table 5: CR in BSSs with unequal stellar-mass components and different eccentricities.

| $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $e^*$ | $CR_{M_1}^{**}$ (sec$^{-1}$) | $CR_{M_2}^{**}$ (sec$^{-1}$) | $CR_M^{***}$ (sec$^{-1}$) | system number |
|-------------------|-------------------|------|-----------------|-----------------|-----------------|----------------|
| 1.0               | 50.0              | 0 (circle) | $T_{115} = 3.5646 \times 10^{23}$ | $T_{136} = 4.2780 \times 10^{27}$ | $T_{115+116} = 4.2784 \times 10^{27}$ | system (55) |
|                   |                   | 0.3          | $T_{117} = 3.2908 \times 10^{23}$ | $T_{118} = 4.4625 \times 10^{27}$ | $T_{117+118} = 4.4628 \times 10^{27}$ | system (56) |
|                   |                   | 0.6          | $T_{119} = 2.6948 \times 10^{23}$ | $T_{120} = 4.5818 \times 10^{27}$ | $T_{119+120} = 4.5821 \times 10^{27}$ | system (57) |
|                   |                   | 0.9          | $T_{121} = 6.6544 \times 10^{22}$ | $T_{122} = 4.6653 \times 10^{27}$ | $T_{121+122} = 4.6654 \times 10^{27}$ | system (58) |
| 50.0              | 1.0               | 0 (circle) | $T_{123} = 4.2780 \times 10^{27}$ | $T_{124} = 3.5646 \times 10^{23}$ | $T_{123+124} = 4.2784 \times 10^{27}$ | system (59) |
|                   |                   | 0.3          | $T_{125} = 3.9553 \times 10^{27}$ | $T_{126} = 3.7214 \times 10^{23}$ | $T_{125+126} = 3.9557 \times 10^{27}$ | system (60) |
|                   |                   | 0.6          | $T_{127} = 3.2511 \times 10^{27}$ | $T_{128} = 3.8228 \times 10^{23}$ | $T_{127+128} = 3.2515 \times 10^{27}$ | system (61) |
|                   |                   | 0.9          | $T_{129} = 8.2445 \times 10^{26}$ | $T_{130} = 3.8938 \times 10^{23}$ | $T_{129+130} = 8.2484 \times 10^{26}$ | system (62) |
| 5.0               | 50.0              | 0 (circle) | $T_{131} = 1.5939 \times 10^{26}$ | $T_{132} = 4.2474 \times 10^{27}$ | $T_{131+132} = 4.4068 \times 10^{27}$ | system (63) |
|                   |                   | 0.3          | $T_{133} = 1.4631 \times 10^{26}$ | $T_{134} = 4.4453 \times 10^{27}$ | $T_{133+134} = 4.5916 \times 10^{27}$ | system (64) |
|                   |                   | 0.6          | $T_{135} = 1.1813 \times 10^{26}$ | $T_{136} = 4.5736 \times 10^{27}$ | $T_{135+136} = 4.6917 \times 10^{27}$ | system (65) |
|                   |                   | 0.9          | $T_{137} = 2.6406 \times 10^{25}$ | $T_{138} = 4.6636 \times 10^{27}$ | $T_{137+138} = 4.6900 \times 10^{27}$ | system (66) |
| 50.0              | 5.0               | 0 (circle) | $T_{139} = 4.2474 \times 10^{27}$ | $T_{140} = 1.5939 \times 10^{26}$ | $T_{139+140} = 4.4068 \times 10^{27}$ | system (67) |
|                   |                   | 0.3          | $T_{141} = 3.9029 \times 10^{27}$ | $T_{142} = 1.6691 \times 10^{26}$ | $T_{141+142} = 4.0698 \times 10^{27}$ | system (68) |
|                   |                   | 0.6          | $T_{143} = 3.1592 \times 10^{27}$ | $T_{144} = 1.7178 \times 10^{26}$ | $T_{143+144} = 3.3310 \times 10^{27}$ | system (69) |
|                   |                   | 0.9          | $T_{145} = 7.1941 \times 10^{26}$ | $T_{146} = 1.7520 \times 10^{26}$ | $T_{145+146} = 8.9461 \times 10^{26}$ | system (70) |
| 1.0               | 5.0               | 0 (circle) | $T_{147} = 3.8703 \times 10^{23}$ | $T_{148} = 1.7422 \times 10^{26}$ | $T_{147+148} = 1.7461 \times 10^{26}$ | system (71) |
|                   |                   | 0.3          | $T_{149} = 3.8341 \times 10^{23}$ | $T_{150} = 1.7510 \times 10^{26}$ | $T_{149+150} = 1.7548 \times 10^{26}$ | system (72) |
|                   |                   | 0.6          | $T_{151} = 3.7450 \times 10^{23}$ | $T_{152} = 1.7565 \times 10^{26}$ | $T_{151+152} = 1.7692 \times 10^{26}$ | system (73) |
|                   |                   | 0.9          | $T_{153} = 3.1768 \times 10^{23}$ | $T_{154} = 1.7603 \times 10^{26}$ | $T_{153+154} = 1.7635 \times 10^{26}$ | system (74) |
| 5.0               | 1.0               | 0 (circle) | $T_{155} = 1.7422 \times 10^{26}$ | $T_{156} = 3.8703 \times 10^{23}$ | $T_{155+156} = 1.7461 \times 10^{26}$ | system (75) |
|                   |                   | 0.3          | $T_{157} = 1.7260 \times 10^{26}$ | $T_{158} = 3.8899 \times 10^{23}$ | $T_{157+158} = 1.7299 \times 10^{26}$ | system (76) |
|                   |                   | 0.6          | $T_{159} = 1.6862 \times 10^{26}$ | $T_{160} = 3.9023 \times 10^{23}$ | $T_{159+160} = 1.6901 \times 10^{26}$ | system (77) |
|                   |                   | 0.9          | $T_{161} = 1.4320 \times 10^{26}$ | $T_{162} = 3.9107 \times 10^{23}$ | $T_{161+162} = 1.4359 \times 10^{26}$ | system (78) |

* Eccentricity.

** CR by $M_1$ star when it is in periastron and when it is in ZAMS phase.

*** CR by $M_2$ star when it is in apastron and when it is in ZAMS phase.

**** Total CR: $CR_M = CR_{M_1} + CR_{M_2}$
• The more the total mass of the binary is \( (M = M_1 + M_2) \) then, the more the CR variation is (and not CR alone) (see section 3.1 for more details).

• By increasing semi-major axis, the total CR increases too (see section 3.2 for more details).

• The more the eccentricity of the systems is then, the more the CR variation is (see section 3.3 for more details). So, CR variation boosted when stars follow elliptical rather than circular orbits.

If DM particles annihilate inside stars then, they can act as a new source of energy inside stars. This new source of energy causes periodic luminosity variations in binary systems. In addition, CR variation can be translated into the neutrino flux variation, as stars (like the sun) are the source of neutrino emissions. These observational considerations are of particular importance for binaries that are located in the high DM density environments (e.g. near the Galactic massive black hole or regions near the center of global clusters).

Besides, observational evidence can be used to constrain the DM properties using the BSSs, which can be the subject of future studies in this respect.

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6 References

References

[1] S. Weinberg. *Cosmology*. Oxford University Press, 2008.

[2] Yoshiaki Sofue and Vera Rubin. Rotation curves of spiral galaxies. *Annu. Rev. Astron. Astrophys.*, 39(1):137–174, sep 2001.

[3] Michael Kuhlen, Mark Vogelsberger, and Raul Angulo. Numerical simulations of the dark universe: State of the art and the next decade. *Phys. Dark Universe*, 1(1-2):50–93, nov 2012.

[4] Julio F. Navarro, Carlos S. Frenk, and Simon D. M. White. The Structure of Cold Dark Matter Halos. *Astrophys. J.*, 462:563, may 1996.

[5] Malcolm Fairbairn, Pat Scott, and Joakim Edsjö. The zero age main sequence of WIMP burners. *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 77(4):47301, feb 2008.

[6] P. C. Scott, J. Edsjö, and M. Fairbairn. Low mass stellar evolution with WIMP capture and annihilation. In H. V. Klapdor-Kleingrothaus and G. T. Lewis, editors, *Proc. 6th Int. Heidelb. Conf. Dark Matter Astropart. Part. Physics, Dark 2007*, pages 387–392. WORLD SCIENTIFIC, apr 2008.

[7] Pat Scott, Malcolm Fairbairn, and Joakim Edsjö. Dark stars at the Galactic Centre - The main sequence. *Mon. Not. R. Astron. Soc.*, 394(1):82–104, mar 2009.

[8] G. Steigman, H. Quintana, C. L. Sarazin, and J. Faulkner. Dynamical interactions and astrophysical effects of stable heavy neutrinos. *Astron. J.*, 83:1050, sep 1978.
[9] J. I. Read, M. G. Walker, and P. Steger. Dark matter heats up in dwarf galaxies. *Mon. Not. R. Astron. Soc.*, 484(1):1401–1420, 2019.

[10] Ebrahim Hassani, Reza Pazhouhesh, and Hossein Ebadi. The effect of dark matter on stars at the Galactic center: The paradox of youth problem. *Int. J. Mod. Phys. D*, 29(8):2050052, jun 2020.

[11] Chris Kouvaris. WIMP annihilation and cooling of neutron stars. *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 77(2):23006, jan 2008.

[12] Chris Kouvaris and Peter Tinyakov. Can neutron stars constrain dark matter? *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 82(6):63531, sep 2010.

[13] Gianfranco Bertone and Malcolm Fairbairn. Compact stars as dark matter probes. *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 77(4):43515, feb 2008.

[14] Zeinab Rezaei. Double dark matter admixed neutron star. *Int. J. Mod. Phys. D*, 27(16):1950002, 2018.

[15] Zeinab Rezaei. Neutron stars with spin polarized self-interacting dark matter. *Astropart. Phys.*, 101:1–7, 2018.

[16] Z. Rezaei. STUDY of DARK-MATTER ADMIXED NEUTRON STARS USING the EQUATION of STATE from the ROTATIONAL CURVES of GALAXIES. *Astrophys. J.*, 835(1):33, 2017.

[17] Andrew Gould. Resonant enhancements in weakly interacting massive particle capture by the earth. *Astrophys. J.*, 321:571, oct 1987.

[18] W. H. Press and D. N. Spergel. Capture by the sun of a galactic population of weakly interacting, massive particles. *Astrophys. J.*, 296:679, sep 1985.

[19] Nicole F. Bell, Giorgio Busoni, Sandra Robles, and Michael Virgato. Improved treatment of dark matter capture in neutron stars. *J. Cosmol. Astropart. Phys.*, 2020(09):028–028, 2020.

[20] Guey Lin Lin and Yen Hsun Lin. Analysis on the black hole formations inside old neutron stars by isospin-violating dark matter with self-interaction. *J. Cosmol. Astropart. Phys.*, 2020(8):022–022, 2020.

[21] Nicole F. Bell, Giorgio Busoni, and Sandra Robles. Capture of leptophilic dark matter in neutron stars. *J. Cosmol. Astropart. Phys.*, 2019(6):54, jun 2019.

[22] Nicole F. Bell, Giorgio Busoni, and Sandra Robles. Heating up neutron stars with inelastic dark matter. *J. Cosmol. Astropart. Phys.*, 2018(9):18, 2018.

[23] A. Nuñez-Castiñeyra, E. Nezri, and V. Bertin. Dark matter capture by the Sun: Revisiting velocity distribution uncertainties. *J. Cosmol. Astropart. Phys.*, 2019(12):43, 2019.

[24] Chian Shu Chen and Yen Hsun Lin. On the evolution process of two-component dark matter in the Sun. *J. High Energy Phys.*, 2018(4):74, apr 2018.

[25] Riccardo Catena. WIMP capture and annihilation in the Earth in effective theories. *J. Cosmol. Astropart. Phys.*, 2017(1):59, 2017.

[26] Jonathan L. Feng, Jordan Smolinsky, and Philip Tanedo. Dark photons from the center of the Earth: Smoking-gun signals of dark matter. *Phys. Rev. D*, 93(1):15014, 2016.

[27] Fei Fan Lee, Guey Lin Lin, and Yue Lin Sming Tsai. Constraining dark matter capture and annihilation cross sections by searching for neutrino signature from the Earth’s core. *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 89(2):25003, 2014.
Capture Rate of Weakly Interacting Massive Particles (WIMPs) In Binary Star Systems

[28] Raghuveer Garani and Peter Tinyakov. Constraints on dark matter from the Moon. *Phys. Lett. Sect. B Nucl. Elem. Part. High-Energy Phys.*, 804:135403, may 2020.

[29] Basudeb Dasgupta, Aritra Gupta, and Anupam Ray. Dark matter capture in celestial objects: improved treatment of multiple scattering and updated constraints from white dwarfs. *J. Cosmol. Astropart. Phys.*, 2019(08):018–018, aug 2019.

[30] Peter W. Graham, Ryan Janish, Vijay Narayan, Surjeet Rajendran, and Paul Riggins. White dwarfs as dark matter detectors. *Phys. Rev. D*, 98(11):115027, 2018.

[31] Vedran Brdar, Joachim Kopp, and Jia Liu. Dark gamma-ray bursts. *Phys. Rev. D*, 95(5):55031, 2017.

[32] A. D. Avrorin, A. V. Avrorin, V. M. Aynutdinov, R. Bannasch, I. A. Belolaptikov, D. Yu Bogorodsky, V. B. Brudanin, N. M. Budnev, I. A. Danilchenko, S. V. Demidov, G. V. Domogatsky, A. A. Doroshenko, A. N. Dyachok, Zh A.M. Dzhilkibaev, S. V. Fialkovsky, A. R. Gafarov, O. N. Gaponenko, K. V. Golubkov, T. I. Gress, Z. Honz, K. G. Kebkal, O. G. Kebkal, K. V. Konischev, E. N. Konstantinov, A. V. Korobchenko, A. P. Koshechkin, F. K. Koshel, A. V. Kozhin, V. F. Kulepov, D. A. Kuleshov, V. I. Ljashuk, M. B. Milenin, R. A. Mirkazov, E. R. Ospova, A. I. Panfilov, L. V. Pan’kov, A. A. Perevalov, E. N. Pliskovsky, V. A. Poleschuk, M. I. Rozanov, V. F. Rubtsov, E. V. Rjabov, B. A. Shabonov, A. A. Sheifler, A. V. Shkurin, A. A. Smagina, O. V. Suvorova, B. A. Tarashansky, S. A. Yakovlev, A. V. Zagorodnikov, V. A. Zhukov, and V. L. Zurbanov. Search for neutrino emission from relic dark matter in the sun with the Baikal NT200 detector. *Astropart. Phys.*, 62:12–20, 2015.

[33] Man Ho Chan and Chak Man Lee. Constraining the spin-independent elastic scattering cross section of dark matter using the Moon as a detection target and the background neutrino data. *Phys. Rev. D*, 102(2):23024, 2020.

[34] Deepak Tiwari, Sandhya Choubey, and Anushree Ghosh. Prospects of indirect searches for dark matter annihilations in the earth with ICAL@INO. *J. High Energy Phys.*, 2019(5):39, 2019.

[35] Stephen L. Adler. Planet-bound dark matter and the internal heat of Uranus, Neptune, and hot-Jupiter exoplanets. *Phys. Lett. Sect. B Nucl. Elem. Part. High-Energy Phys.*, 671(2):203–206, 2009.

[36] L. Iorio. Effect of sun and planet-bound dark matter on planet and satellite dynamics in the solar system. *J. Cosmol. Astropart. Phys.*, 2010(5):18, 2010.

[37] Axel Widmark. Thermalization time scales for WIMP capture by the Sun. *Proc. Sci.*, ICRC2017:916, 2017.

[38] Giorgio Busoni, Andrea De Simone, Pat Scott, and Aaron C. Vincent. Evaporation and scattering of momentum- and velocity-dependent dark matter in the Sun. *J. Cosmol. Astropart. Phys.*, 2017(10), oct 2017.

[39] Ilídio Lopes, Jordi Casanellas, and Daniel Eugénio. The capture of dark matter particles through the evolution of low-mass stars. *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 83(6):63521, mar 2011.

[40] Cosmin Ilie and Saiyang Zhang. Multiscatter capture of superheavy dark matter by Pop III stars. *J. Cosmol. Astropart. Phys.*, 2019(12):51, 2019.

[41] Joseph Bramante, Antonio Delgado, and Adam Martin. Multiscatter stellar capture of dark matter. *Phys. Rev. D*, 96(6):63002, 2017.

[42] Marco Taoso, Gianfranco Bertone, Georges Meynet, and Silvia Ekström. Dark matter annihilations in Population III stars. *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 78(12):123510, dec 2008.

[43] Jordi Casanellas and Ilídio Lopes. The formation and evolution of young low-mass stars within halos with high concentration of dark matter particles. *Astrophys. J.*, 705(1):135–143, nov 2009.
[44] Dan Hooper, Douglas Spolyar, Alberto Vallinotto, and Nickolay Y. Gnedin. Inelastic dark matter as an efficient fuel for compact stars. *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 81(10):103531, may 2010.

[45] Chris Kouvaris and Peter Tinyakov. Constraining asymmetric dark matter through observations of compact stars. *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 83(8):83512, apr 2011.

[46] Paolo Pani. Binary pulsars as dark-matter probes. *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, 92(12):123530, 2015.

[47] L. Gabriel Gómez and J. A. Rueda. Dark matter dynamical friction versus gravitational wave emission in the evolution of compact-star binaries. *Phys. Rev. D*, 96(6):63001, 2017.

[48] L. Gabriel Gómez. Constraining light fermionic dark matter with binary pulsars. *Phys. Dark Universe*, 26:100343, 2019.

[49] Andrea Caputo, Jesús Zavala, and Diego Blas. Binary pulsars as probes of a Galactic dark matter disk. *Phys. Dark Universe*, 19:1–11, mar 2018.

[50] Basudeb Dasgupta, Aritra Gupta, and Anupam Ray. Dark matter capture in celestial objects: light mediators, self-interactions, and complementarity with direct detection. jun 2020.

[51] Bill Paxton, Matteo Cantiello, Phil Arras, Lars Bildsten, Edward F. Brown, Aaron Dotter, Christopher Mankovich, M. H. Montgomery, Dennis Stello, F. X. Timmes, and Richard Townsend. Modules for experiments in stellar astrophysics (MESA): Planets, oscillations, rotation, and massive stars. *Astrophys. Journal, Suppl. Ser.*, 208(1):4, sep 2013.

[52] Bill Paxton, Josiah Schwab, Evan B. Bauer, Lars Bildsten, Sergei Blinnikov, Paul Duffell, R. Farmer, Jared A. Goldberg, Pablo Marchant, Elena Sorokina, Anne Thoul, Richard H. D. Townsend, and F. X. Timmes. Modules for Experiments in Stellar Astrophysics ($\{Journal of something\{M\}\}|\{Journal of something\{E\}\}|\{Journal of something\{S\}\}|\{Journal of something\{A\}\}$): Convective Boundaries, Element Diffusion, and Massive Star Explosions. *Astrophys. J. Suppl. Ser.*, 234(2):34, 2018.

[53] Bill Paxton, Pablo Marchant, Josiah Schwab, Evan B. Bauer, Lars Bildsten, Matteo Cantiello, Luc Dessart, R. Farmer, H. Hu, N. Langer, R. H.D. Townsend, Dean M. Townsley, and F. X. Timmes. Modules for Experiments in Stellar Astrophysics (MESA): Binaries, pulsations, and explosions. *Astrophys. Journal, Suppl. Ser.*, 220(1):15, sep 2015.

[54] Aaron Dotter. Mesa Isochrones and Stellar Tracks (Mist) 0: Methods for the Construction of Stellar Isochrones. *Astrophys. J. Suppl. Ser.*, 222(1):8, 2016.

[55] Bill Paxton, R. Smolec, Josiah Schwab, A. Gautoch, Lars Bildsten, Matteo Cantiello, Aaron Dotter, R. Farmer, Jared A. Goldberg, Adam S. Jermy, S. M. Kanbur, Pablo Marchant, Anne Thoul, Richard H. D. Townsend, William M. Wolf, Michael Zhang, and F. X. Timmes. Modules for Experiments in Stellar Astrophysics (MESA): Pulsating Variable Stars, Rotation, Convective Boundaries, and Energy Conservation. *Astrophys. J. Suppl. Ser.*, 243(1):10, 2019.

[56] Bill Paxton, Lars Bildsten, Aaron Dotter, Falk Herwig, Pierre Lesaffre, and Frank Timmes. Modules for Experiments in Stellar Astrophysics (MESA). *Astrophys. Journal, Suppl. Ser.*, 192(1):3, jan 2011.

[57] R. W. Hilditch. *An Introduction to Close Binary Stars*. Cambridge University Press, mar 2001.

[58] Francesco Capozzi, Ian M. Shoemaker, and Luca Vecchi. Solar neutrinos as a probe of dark matter-neutrino interactions. *J. Cosmol. Astropart. Phys.*, 2017(7):21, 2017.
[59] Sebastian Baum, Luca Visinelli, Katherine Freese, and Patrick Stengel. Dark matter capture, subdominant WIMPs, and neutrino observatories. *Phys. Rev. D*, 95(4):43007, Feb 2017.

[60] Kohta Murase and Ian M. Shoemaker. Detecting asymmetric dark matter in the Sun with neutrinos. *Phys. Rev. D*, 94(6):63512, Sep 2016.

[61] Wan Lei Guo. Detecting electron neutrinos from solar dark matter annihilation by JUNO. *J. Cosmol. Astropart. Phys.*, 2016(1):39, 2016.

[62] Carlos Pérez De Los Heros. The quest for dark matter with neutrino telescopes. In *Neutrino Astron. Curr. Status, Futur. Prospect.*, pages 155–171. 2017.