Tidal deformability of dark matter admixed neutron stars

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Abstract

Keywords:

1. Introduction

It is generally accepted that dark matter constitutes the bulk of the universe's mass. However, its properties remain largely unknown. Observational evidences, such as the flat rotation curves of spiral galaxies [1], gravitational lensing effects [2], and the anisotropies in the cosmic microwave background [3], strongly suggests the presence of dark matter.Several major experiments are actively investigating dark matter particles to uncover their characteristics, including XENON1T [4], LUX-ZEPLIN (LZ) [5], and the China Dark Matter Experiment (CDEX) [6].Uncovering the true nature of dark matter would mark a major breakthrough in physics.

Dark matter neither emits light nor interacts in ways that would produce light or any other form of electromagnetic radiation. It doesn't engage in interactions with itself or ordinary baryonic matter aside from gravitational forces. Given the weakness of gravitational interactions, detecting dark matter through its gravitational effects on normal matter is exceptionally challenging.On cosmological scales, studying dark matter becomes more feasible because its gravitational effects are prominent over vast distances and within large structures, making it easier to detect.High-density areas, where both dark matter and visible matter are more concentrated, also provide strong gravitational fields that make dark matter's presence and effects more noticeable.

Compact stars, particularly neutron stars, serve as valuable natural laboratories for dark matter research. Their extreme densities and intense gravitational environments create conditions that could amplify interactions or reveal the effects of accumulated dark matter, offering unique insights into its properties.

In neutron star cores, the conditions reach such extreme levels of density and gravitational strength that deriving the EOS directly from fundamental physics principles, like Quantum Mechanics or Quantum Chromodynamics, becomes exceedingly complex. To address this, scientists rely on experimental data—such as results from nuclear reactions in particle accelerators—and observational data, including neutron star mass-radius measurements [7] and tidal deformability [8], to narrow down and place limits on the possible EOS models. Observations have shown that neutron stars with masses around $2M_\odot$ [9] have eliminated many equations of state (EOS) that predict maximum neutron star masses below $2M_\odot$ The first gravitational-wave detection, GW170817, from a binary neutron star merger [10], has provided valuable constraints on the tidal properties of neutron stars, sparking numerous studies [11, 12, 13] on its implications.The gravitational-wave event GW190814 [14] marked the detection of a compact object with an unusually high mass of $2.6M_\odot$ in a binary merger with a black hole. The nature of this $2.6M_\odot$ compact object is still under investigation. According to recent studies, it may be either a massive neutron star [15, 16] or a black hole [17, 18].Observations have shown that neutron stars with masses around $2M_\odot$ [9] have eliminated many equations of state (EOS) that predict maximum neutron star masses below $2M_\odot$.The first gravitational-wave detection, GW170817, from a binary neutron star merger [10], has provided valuable constraints on the tidal properties of neutron stars, sparking numerous studies [11, 12, 13] on its implications.The gravitational-wave event GW190814 [14] marked the detection of a compact object with an unusually high mass of $2.6M_\odot$ in

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a binary merger with a black hole. The nature of this 2.6$M_\odot$ compact object is still under investigation. According to recent studies, it may be either a massive neutron star [15, 16] or a black hole [17, 18]. Recent measurements of the mass and radius of several pulsars, such as PSR J0030+0451, obtained from the NICER X-ray telescope, have significantly improved our astrophysical constraints on the equation of state (EoS) of cold, catalyzed matter above nuclear saturation density [19, 20].These findings also enhance our understanding of the properties of dense matter in the cores of neutron stars [21]. Hence we will gain more valuable information about the equation of state (EOS) for unknown nuclear matter in the next decade through more observations of neutron star.

Neutron stars generate a powerful gravitational field due to their extremely high central density, which can draw in or capture dark matter particles.Since dark matter interacts with normal matter of neutron stars only through gravity, it could affect various properties of neutron stars, such as their mass, radius, and tidal deformability etc.This opens up the exciting possibility of using neutron stars as natural laboratories to indirectly study and measure dark matter properties.Till now various studies have done on effect of dark matter on neutron star properties [22, 23, 24, 25, 26, 27, 28, 29].A new class of compact objects dominated by dark matter has been identified, featuring a nuclear matter core surrounded by a ten-kilometer dark matter halo. This discovery arose from studying the equilibrium configuration of degenerate dark matter and nuclear matter using a relativistic two-fluid model[22]. By the same approach the static configurations and tidal properties of dark matter admixed neutron stars have been discussed [23].This study shows that the dimensionless tidal deformabilty changes sharply with increase in dark matter mass fraction in intermediate interval.So the study of the tidal properties of neutron stars containing dark matter may provide new insights into the characteristics of dark matter parameters and help reveal various unknown properties of dark matter.

2. Method

2.1. *Hydrostatic configuration*

The form of metric that describes a static spherically spacetime is

$$ds^2 = -e^{\nu(r)}dt^2 + e^{\lambda(r)}dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 \quad (1)$$

The equation for static,spherically symmetric,non rotating compact star can be obtained from this metric and this equation is called Tolman-Oppenheimer-Volkoff equation(TOV)[30]:

$$\frac{dp}{dr} = -\frac{m(r) + 4\pi r^3 p(r)}{r^2(1 - \frac{2m(r)}{r})}(\rho(r) + P(r)) \quad (2)$$

Also the equation that describes how the enclosed mass m(r) at a given radius r changes as we move outward from the center of the star is

$$\frac{dm}{dr} = 4\pi r^2 \rho(r) \quad (3)$$

Here $m(r)$ is the mass of the compact object enclosed within a radial distance r and $\rho(r)$ is its energy density at distance r.Also $m(r)$ is related by the metric function $\lambda(r)$ through a relation $e^{-\lambda(r)} = 1 - \frac{2m(r)}{r}$.The derivative of the metric function $\nu(r)$ can be connected with the star's mass, radius and pressure by the relation

$$\frac{d\nu}{dr} = \frac{2(m(r) + 4\pi p(r) r^3)}{r^2(1 - \frac{2m(r)}{r})} \quad (4)$$

The boundary conditions for the equations (2) and (3) are at the centre of the star its mass is zero i.e.,$m(r = 0) = 0$ and star having a density at its centre called central density,$\rho(r = 0) = \rho_c$.It can be shown that on the star's surface the metric function $\nu(r)$ satisfies $e^{\nu(R)} = 1 - \frac{2M}{R}$,where M is the total mass of the star and R is its total radius. For the study of DANS (Dark matter admixed neutron star) using Two-fluid model we have to modify the TOV equation a little bit.One of the assumption we have made that there is no interaction between normal matter and dark matter occurs except gravitational interaction between them.Therefore the energy density can be expressed in the form:

$$\rho(N_{nm}, N_{dm}) = \rho_{nm}(N_{nm}) + \rho_{dm}(N_{dm}) \quad (5)$$

i.e., the energy density is sum of the energy density of normal matter and that of the dark matter.Like energy density the expression of pressure also includes two parts, the pressure of NM and that of DM [31].

$$P(N_{nm}, N_{dm}) = P_{nm}(N_{nm}) + P_{dm}(N_{dm}) \quad (6)$$

We will solve the TOV equation here using two fluid model. In this model it is assumed that the dark matter and baryonic matter are interacting each other only via gravity.

The TOV equation and mass equation in this model are [31, 23, 32]:

$$\frac{dP_{nm}}{dr} = -(P_{nm} + \rho_{nm})\frac{d\nu}{dr} \quad (7)$$

$$\frac{dm_{nm}}{dr} = 4\pi r^2 \rho_{nm} \quad (8)$$

$$\frac{dP_{dm}}{dr} = -(P_{dm} + \rho_{dm})\frac{d\nu}{dr} \quad (9)$$

$$\frac{dm_{dm}}{dr} = 4\pi r^2 \rho_{dm} \quad (10)$$

$$\frac{d\nu}{dr} = \frac{(m_{nm} + m_{dm}) + 4\pi r^3 (p_{nm} + p_{dm})}{r(r - 2(m_{nm} + m_{dm}))} \quad (11)$$

The index "nm" stands for normal matter and index "dm" stands for dark matter.The systems of above equations will be solved along with differential equation for the tidal deformability and second love number k_2 . The boundary conditions of the above system of equations are:

$$m_{nm}(r = 0) = 0 \quad (12)$$

$$\rho_{nm}(r = 0) = \rho_{c,nm} \quad (13)$$

$$m_{dm}(r = 0) = 0 \quad (14)$$

$$\rho_{dm}(r = 0) = \rho_{c,dm} \quad (15)$$

The radial distance from the center,where both the dark matter pressure and normal matter pressure vanish gives us the star's total radius R.We can restore the exact form of TOV equation by summing the normal matter component and dark matter component.

2.2. *The tidal deformability and tidal Love number*

The newest addition to astrophysical methods for probing properties of neutron star focuses on examining its tidal response.The neutron star shape is distorted under the effect of an external perturbing tidal gravitational field created by its own companion star.This change in shape is measured by a parameter known as tidal deformability λ_{tid}.Mathematically it is defined as the ratio of the induced quadrupole moment tensor(Q_{ij}) to the perturbing tidal field tensor (ϵ_{ij}) that causes the perturbation.

$$\lambda_{tid} = -\frac{Q_{ij}}{\epsilon_{ij}} \quad (16)$$

For non rotating star,the determination of tidal deformability is given in many articles[33, 34, 35].

We outline the primary equations here and recommend Refs. [33–35] for additional information.The expression of tidal love number can be written as follows:

$$\begin{aligned} k_2 = {} & \frac{8}{5}\beta^5(1-2\beta)^2\left[2 - y_R + 2\beta(y_R - 1)\right] \\ & \times \left[2\beta(6 - 3y_R + 3\beta(5y_R - 8))\right. \\ & + 4\beta^3[13 - 11y_R + \beta(3y_R - 2) + 2\beta^2(1 + y_R)] \\ & \left. + 3(1-2\beta)^2[2 - y_R + 2\beta(y_R - 1)]\log(1-2\beta)\right]^{-1}. \end{aligned} \quad (17)$$

Here $\beta = \frac{M}{R}$ is the dimensionless compactness parameter and $y_R = \frac{rH'(r)}{H(r)}|_{r=R}$,The function H(r) is basicaly a solution obtained by solving the following differential equation:

$$H''(r) + H'(r)F(r) + H(r)Q(r) = 0 \quad (18)$$

where,

$$F(r) = \frac{2}{r} + e^{\lambda(r)}\left(\frac{2m(r)}{r^2} + 4\pi r(p(r) - \rho(r))\right) \quad (19)$$

$$Q(r) = -\frac{6e^{\lambda}}{r^2} + 4\pi e^{\lambda}\left(5\rho + 9p + \frac{\rho + p}{\left(\frac{dp}{d\rho}\right)}\right) - \nu'^2 \quad (20)$$

The primes indicate spatial derivatives and $\lambda(r)$ and $\nu(r)$ are the metric functions defined as:

$$e^{\lambda(r)} = \left(1 - \frac{2m(r)}{r}\right)^{-1} \quad (21)$$

In terms of $y(r)$ the equation (18) takes form:

$$\begin{aligned} ry'(r) + y^2(r) + y(r)e^{\lambda}(r)[1 + 4\pi r^2(p(r) - \rho(r))] \\ + r^2 Q(r) = 0 \end{aligned} \quad (22)$$

The boundary condition of the above equation is $y(r = 0) = 2$. After solving the equation both outside and inside the star, two solutions were found. Upon matching the two solutions at the surface of the star, the expression for the quadrupolar tidal Love number $(Eq.17)$ was obtained.The perturbing tidal field (ϵ_{ij}) has unit of inverse length squared[36].The unit of quadrupole moment is cube of length.So tidal deformability is written as:

$$\lambda = \frac{2}{3}k_2 R^5 \quad (23)$$

where k_2 is well known quadrupolar Love number and R is star's radius.

The dimensionless tidal deformability is also used in many cases.It is defined as

$$\Lambda \equiv \frac{\lambda}{M^5} = \frac{2}{3} k_2 \frac{R^5}{M^5} = \frac{2}{3} k_2 \beta^{-5} \tag{24}$$

where M is mass of the star and β is its compactness.

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