Dark Compact Planets

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We investigate compact objects formed by dark matter admixed with ordinary matter made of neutron star matter and white dwarf material. We consider non-self annihilating dark matter with an equation-of-state given by an interacting Fermi gas. We find new stable solutions, dark compact planets, with Earth-like masses and radii from few Km to few hundred Km for weakly interacting dark matter which are stabilized by the mutual presence of dark matter and compact star matter. For the strongly interacting dark matter case, we obtain dark compact planets with Jupiter-like masses and radii of few hundred Km. These objects could be detected by observing exoplanets with unusually small radii. Moreover, we find that the recently observed 2 M_⊙ pulsars set limits on the amount of dark matter inside neutron stars which is, at most, 10^{-6}M_⊙.

Astrophysical and cosmological observations reveal that most of the mass of the universe is in the form of dark matter (DM) [1, 2]. The nature of dark matter is still elusive. There are direct methods for detecting DM using particle accelerators [3, 4] or analyzing DM scattering off nuclear targets in terrestrial detectors [5], such as CDMS-II [6], CREST-II [7], CoGENT [8], DAMA/LiBRA [9], LUX [10], SIMPLE [11], XENON10/100 [12], and SuperCDMS [13].

Apart from these direct searches, constraints on the properties of DM can be extracted by studying DM stars [14, 15] or the effects of DM on compact objects, such as white dwarfs and neutron stars. Neutron stars are the densest observable objects in the universe and, thus, a privileged laboratory for the exploration of matter under extreme conditions. The structure of neutron stars is determined by the equation-of-state (EoS), which is well constrained up to normal nuclear saturation density [16]. However, the properties of matter at supranormal densities are unknown while being fundamental for the determination of the maximum mass of neutron stars. Recent accurate measurements of 2M_⊙ neutron stars [17, 18] are setting some tension among different determinations of EoS and, hence, the structure of neutron stars.

The possible gravitational collapse of a neutron star due to accretion of DM can set bounds on the mass of DM candidates [19, 20]. Also, constraints on DM can be obtained from stars that accrete asymmetric DM during their lifetime and then collapse into a white dwarf or neutron star, inheriting the accumulated DM [21]. Moreover, the cooling process of compact objects can be affected by the capture of DM, which subsequently annihilates heating the star [22–26]. At the same time, self-annihilating DM accreted onto neutron stars may affect significantly their kinematical properties [27] or provide a mechanism to see compact objects with long-lived lumps of strangelets [28]. Therefore, it is of high interest to analyze the effects of DM on compact stellar objects.

Recently, neutron stars with non-self annihilating DM have emerged as an interesting astrophysical scenario, where to analyze the gravitational effects of DM onto ordinary matter (OM) under extreme conditions [26, 29–33]. In [30] the two-fluid system of mirror DM and normal matter coupled through gravity was considered. An admixture of degenerate DM with masses of ~1 GeV and normal matter was studied in [31] using a general relativistic two-fluid formalism. Also, in [32] the approach of [30] was followed with various masses in the GeV range for DM and different interactions. DM admixed white dwarfs were discussed in [34] assuming an ideal degenerate Fermi gas for non-self annihilating DM.

In this paper we investigate compact objects formed by DM admixed with neutron star matter but also with white dwarf material. We solve the two-fluid system of DM and OM coupled gravitationally while performing, for the first time, a stability analysis of the DM admixed objects for non-self annihilating DM with a particle mass of 100 GeV [35, 36]. We find new stable solutions of the Tolman-Oppenheimer-Volkoff (TOV) equations with planet-like objects of Earth-like masses and radii from few Km to few hundred Km for weakly interacting DM. For the strongly interacting DM case, we obtain planets with Jupiter-like masses and radii of few hundred Km. These dark compact planets could be detected via exoplanet searches [37] or using gravitational microlensing [38–41]. The detection of an unusually small radius im-

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plying an enormously high mass density would reveal a compact planet, much in the same way as the first detection of white dwarfs. Finally, we explore the DM content that neutron stars of $2\, M_\odot$ [17, 18] might sustain.

In order to analyze the dark compact objects formed by the admixture of OM with DM, one has to solve the TOV equations for a system of two different species that interact gravitationally. One proceeds by solving the dimensionless coupled TOV equations [42] for OM and DM,

$$
\frac{dp'_{OM}}{dr} = -(p'_{OM} + \rho'_{OM}) \frac{dv}{dr},
$$

$$
\frac{dm_{OM}}{dr} = 4\pi r^2 \rho'_{OM},
$$

$$
\frac{dp'_{DM}}{dr} = -(p'_{DM} + \rho'_{DM}) \frac{dv}{dr},
$$

$$
\frac{dm_{DM}}{dr} = 4\pi r^2 \rho'_{DM},
$$

$$
\frac{dv}{dr} = \frac{(m_{OM} + m_{DM}) + 4\pi r^3 (p'_{OM} + p'_{DM})}{r(r - 2(m_{OM} + m_{DM}))},
$$

(1)

where $\rho'$ and $\rho'$ are the dimensionless pressure and energy density, respectively, defined as $\rho' = P/m_f^3$ and $\rho' = \rho/m_f^2$, with $m_f$ being the mass of the fermion, that is the neutron mass and dark matter particle mass, respectively. The physical mass and radius for each species are $R = (M_f/m_f^2) r$ and $M = (M_F^3/m_f^2) m$, respectively, where $M_F$ is the Planck mass [42].

For OM, we consider neutron star matter given by the equation-of-state EoS from [44]. The EoSs obtained in [44] are constrained by using input from low-energy nuclear physics, the high-density limit from perturbative QCD, and observational pulsar data. In particular, the EoS is the most compact one with maximum masses of $2M_\odot$. We, moreover, map EoS with an inner and outer crust EoS using [45] and [46], respectively. For $\rho < 3.3\times 10^3\, \text{g/cm}^3$ we use the Harrison-Wheeler EoS [47]. For DM, the EoS is taken from [42] for a non-annihilating massive DM particle of 100 GeV, in line with several scenarios for DM, such as asymmetric DM, that involve massive particles which cannot annihilate with themselves [15, 48–51]. Two cases are studied, weakly and strongly interacting DM. The strength of the interaction is measured by the strength parameter, $y = m_f/m_I$, which is defined as the ratio between the fermion mass $m_f$ and the interaction mass scale $m_I$ (see Eqs. (34–35) in Ref. [42]). For strong interactions, $m_I \sim 100\, \text{MeV}$ (interaction scale related to the exchange of vector mesons) while for weak interactions $m_I \sim 300\, \text{GeV}$ (exchange of W and Z bosons). Thus, we take $y = 10^{-1}$ and $y = 10^3$ for weakly and strongly interacting DM, respectively.

For the determination of the dark compact objects, one first has to perform an analysis of the stable configuration for both OM and DM. The stability arguments can be found, for example, in [43], where the stability of the different radial modes in a star is analyzed. However, we present here a short description of the stability criteria. We consider small radial perturbations of the equilibrium configuration, which leads to a Sturm-Liouville eigenvalue equation [43]. By solving this equation, we find that the eigenfrequencies of the different modes form a discrete hierarchy $\omega_n^2 < \omega_{n+1}^2$ with $n=0,1,2...$, being $\omega_n$ real numbers. A negative value of $\omega_n^2$ leads to an exponential growth of the radial perturbation and collapse of the star. The determination of the sign of the mode results from the analysis of the mass of the star versus the mass density or radius [43]. The extrema in the mass versus mass density (pressure) indicates a change of sign of the eigenfrequency associated to a certain mode and, hence, a change of stability of the star for a given mass density (pressure). The derivative of the radius versus the mass density at that mass density determines if the change of stability takes place for an even mode (negative derivate) or for an odd mode (positive derivate). Thus, starting at low mass densities where all modes are positive, one can perform the stability analysis for higher mass densities studying the change of sign of the different modes while keeping the hierarchy among them. Only when all eigenfrequencies are positive, the star will be stable. In this way, one can study the stable regions for both OM and DM.

In Fig. 1 we present this analysis for a ratio of the dimensionless central pressures for DM and OM equal to
For a small ratio of $\frac{\rho_{DM}}{\rho_{OM}} = 10^{-4}$, we obtain a new type of objects, hereafter named dark compact planets (DCPs), with Earth-like masses of $M = 10^{-4} - 10^{-7} M_\odot$ and radii from few km to few hundred km. As for the strongly interacting case, these DCPs can reach masses similar to the Jupiter mass, ranging from $10^{-2} - 10^{-5} M_\odot$, and have radii of few hundred km. The DM content of these DCPs ranges from $M = 10^{-3} - 10^{-8} M_\odot$ for Earth-like planets, and $M = 10^{-1} - 10^{-5} M_\odot$ for Jupiter-like ones. Interestingly, by choosing a mass of few GeVs for the DM particle, we obtain DCPs of similar size but much more massive, thus, more compact. Note that by rescaling the EoS for the crust with the iron mass, we reproduce similar results for our DCPs if we increase the pressure of the dark matter relatively to the pressure of ordinary matter. Also, by taking the iron mass instead of neutron mass, it will give a shift in the maximum mass of white dwarfs of the order of the binding energy per baryon relative to the nucleon mass, i.e. below 1%.

At this point, one should consider the different possibilities of having compact stellar objects with DM content, that is, by means of the accretion mechanisms of DM onto neutron stars and white dwarfs as well as by the primordial formation of DM clumps surrounded by OM due to free streaming. On one hand, one can estimate the DM accreted in neutron stars and white dwarfs by using the accretion rate of heavy DM particles onto a neutron star [21, 28] and a white dwarf [21]. A maximum limit for the total accreted mass of DM of $10^{-14} M_\odot$ is obtained for neutron stars, whereas in white dwarfs the maximum total DM mass accreted is $10^{-12} M_\odot$. Thus, the accretion mechanism cannot explain the existence of a DCP. Free streaming estimates of 1 pc [52], on the other hand, give a lower limit for a total DM mass of $10^{-7} M_\odot$. Interestingly, limits on primordial DM objects from Kepler [53] and by the Experience pour la Recherche d’Objets Sombres (EROS) collaboration [54] rule out the mass range of $2 \times 10^{-9}$ to $10^{-7} M_\odot$ and $0.6 \times 10^{-7}$ to $15 M_\odot$, respectively, to constitute the entirety of DM in the Milky Way. However, it is still not ruled out that a fraction of DM form primordially dark compact objects and accrete white dwarf material subsequently, thereby producing a DCP that becomes observable with visible light. A detailed analysis of the primordial formation of our DCPs will be done elsewhere [55].

The search of a DCP could be done in a similar manner as for extrasolar planets (exoplanets). Most of them have been discovered using radial velocity or transit methods. The observation of a DCP using these techniques is provided by measuring an unusually small upper limit to the radius from transiting planets. Gravitational microlensing, as seen by the MASSive Compact Halo Object (MACCHO) project [38], the Microlensing Observations in Astrophysics (MOA) [39], the Optical Gravitational Lensing Experiment (OGLE) [40] or EROS [54], could be an

![Fig. 2: The total mass of the dark compact object as a function of the observable radius (radius of OM) for different ratios of pressures between DM and OM. Two different strengths for the interacting DM are used: $y = 10^{-1}$ (left column) and $y = 10^3$ (right column).](image)

$\frac{\rho_{DM}}{\rho_{OM}} = 10^{-4}$ and the weakly interacting DM case ($y = 10^{-1}$) as a function of the OM central pressure. We show with solid lines the stable mass-radius regions for OM and DM, separately, while the vertical dashed lines delimit the common stable regions for both species (denoted with ”stable” legend). We distinguish two common stable mass-radius regions, one for OM central pressures below $10^{-6} \text{MeVfm}^{-3}$ and another one for OM central pressures above $10^{-1} \text{MeVfm}^{-3}$. A similar analysis has been done for other ratios of pressures and the strongly interacting DM case, obtaining similar results.

Once the stability analysis is performed, we study the structure of the obtained dark compact objects, calculating the total mass of the object as a function of the visible radius, that is, the radius of OM, in an equivalent manner as done for neutron stars or white dwarfs. Neutron stars and white dwarfs exhibit different mass-radius relationships due to their composition and, hence, EoS. While neutron stars have typical masses of 1-2 $M_\odot$ and radius of 10 Km, white dwarfs are characterised by masses of 1$M_\odot$ and radii of few thousand Km.

In Fig. 2 we present the mass-radius relationships of the dark compact objects for different values of the ratio of DM versus OM dimensionless central pressures as well as the weakly and strongly interacting DM cases. For a small ratio of $\frac{\rho_{DM}}{\rho_{OM}} = 10^{-4}$, we observe two stable mass-radius configurations, that correspond to the neutron-star and white-dwarf branches of OM. As the central pressure of DM increases, the neutron-star branch becomes unstable and we are left with the white-dwarf branch, with densities for OM below the neutron drip line but unconventional masses and radii. Indeed, for the weakly interacting DM case and $\frac{\rho_{DM}}{\rho_{OM}} = 10^4$, we obtain a new type of objects, hereafter named dark compact planets (DCPs), with Earth-like masses of $M = 10^{-4} - 10^{-7} M_\odot$ and radii from few km to few hundred km. As for the strongly interacting case, these DCPs can reach masses similar to the Jupiter mass, ranging from $10^{-2} - 10^{-5} M_\odot$, and have radii of few hundred km. The DM content of these DCPs ranges from $M = 10^{-3} - 10^{-8} M_\odot$ for Earth-like planets, and $M = 10^{-1} - 10^{-5} M_\odot$ for Jupiter-like ones. Interestingly, by choosing a mass of few GeVs for the DM particle, we obtain DCPs of similar size but much more massive, thus, more compact.
alternative tool for detecting a DCP.

It is also interesting to study the effect of DM on the 2M⊙ recent observations of neutron stars [17, 18], in order to determine the amount of DM that such massive neutron stars can sustain. In Fig. 3, we display the total mass of the dark compact object as a function of the mass of DM for the strength parameter y = 10^{-1} and for the neutron-star and white-dwarf branches. We observe that as the DM content reaches masses beyond 10^{-6}M⊙, a neutron star with 2M⊙ can not be obtained. There is even a more stringent limit in the DM content coming from the reduction of the nominal mass of white dwarf of 1M⊙. Similar results for the white-dwarf branch are found for the strongly interacting DM case, while the maximum mass for neutron star is below 2M⊙ for DM masses > 10^{-8}M⊙.

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Erratum: "Dark Compact Planets"

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We have discovered an error in our code for solving the dimensionless Tolman-Oppenheimer-Volkov (TOV) equations for a system formed by ordinary matter (OM) and dark matter (DM) that only interact gravitationally. Following the work of Ref. [1] for the determination of the dimensionless TOV equations for one specie, the dimensionless TOV equations for two species read

\[
\frac{dp_{OM}^\prime}{dr} = -(p_{OM}^\prime + p_{OM}) \frac{dv}{dr},
\]

\[
\frac{dm_{OM}}{dr} = 4\pi r^2 \rho_{OM},
\]

\[
\frac{dp_{DM}^\prime}{dr} = -(p_{DM}^\prime + p_{DM}) \frac{dv}{dr},
\]

\[
\frac{dm_{DM}}{dr} = 4\pi r^2 \rho_{DM}^\prime,
\]

\[
\frac{dv}{dr} = \frac{(m_{OM} + m_{DM}) + 4\pi r^3 (p_{OM}^\prime + p_{DM}^\prime)}{\rho_{DM} m_{DM}^\prime}, \quad (1)
\]

where \( p' \) and \( \rho' \) are the dimensionless pressure and energy density of each specie. In order to obtain these dimensionless quantities for each specie one has to divide the physical quantities by one of the physical masses, that is, by the neutron mass or the dark matter particle mass. We erroneously divided the physical quantities for ordinary matter by the neutron mass and those for dark matter by the dark matter particle mass. Given the freedom in choosing the particle mass, we have decided to use the dark matter particle mass, so that \( p_{OM}^\prime = \frac{P_{OM}}{m_D^2} \) and \( \rho_{OM}^\prime = \frac{\rho_{OM}}{m_D^2} \) as well as \( p_{DM}^\prime = \frac{P_{DM}}{m_D^2} \) and \( \rho_{DM}^\prime = \frac{\rho_{DM}}{m_D^2} \), with \( m_D \) being the dark matter particle mass. The physical mass and radius for each specie are then given by \( R_{OM} = (M_p/m_D^2) r_{OM} \) and \( M_{OM} = (\rho_{OM}/m_D^2) m_{OM} \) together with \( R_{DM} = (M_p/m_D^2) r_{DM} \) and \( M_{DM} = (\rho_{DM}/m_D^2) m_{DM} \), where \( M_p \) is the Planck mass [1]. Therefore, the plots have changed, although the results and conclusions are qualitatively similar, as we discuss in the following. In particular, we still find dark compact planets with Earth-like or Jupiter-like masses, depending on the strength of the interacting dark matter, but with radii smaller by four orders of magnitude than those found in Ref. [2].

In Fig. 1 we present an example of the analysis of the stable configuration of both OM and DM. In this case, the calculation is performed for the strongly interacting DM case, with a strength parameter \( y = 10^3 \), and the ratio of dimensionless pressures between DM and OM is equal to \( 10^2 \).

In Fig. 2 we present the corrected figure for the mass-
radius relationships of the dark compact objects for different values of the ratio of DM versus OM dimensionless central pressures as well as the weakly and strongly interacting DM cases. Our results are qualitatively the same as in Fig. 2 of Ref. [2], although the stable mass-radius configurations appear at larger $p_{DM}'/p_{OM}'$ ratios and the values of the observable radii (radius of ordinary matter) are four orders of magnitude smaller than those shown in that previous figure. With the correct rescaling the gravitational effects from DM on OM, in particular on white dwarf matter, those effects are now much more pronounced leading to much smaller radii as compared to our previous calculations in Ref. [2]. Two stable mass-radius configurations, that correspond to the neutron-star and white-dwarf branches of OM, are observed for ratios below $p_{DM}'/p_{OM}' = 10^8$ in the weakly interacting case ($y = 10^{-1}$) and $p_{DM}'/p_{OM}' = 10^4$ in the strongly interacting case ($y = 10^3$). As seen in Fig. 2 of Ref. [2] and corroborated here, only one branch survives for larger ratios of pressure, with densities for OM below the neutron drip line for the largest pressure ratios, but unconventional masses and radii. Those are the dark compact planets (DCPs), with Earth-like masses of $M \sim 10^{-4} - 10^{-6} M_\odot$ or lower, but radii about one meter for the weakly interacting DM case. As for the strongly interacting case, these DCPs can reach masses similar to the Jupiter mass of $10^{-2} - 10^{-4} M_\odot$ or lower, and have radii of a kilometer. The DM content of these DCPs ranges from $M \sim 10^{-4} - 10^{-8} M_\odot$ for Earth-like planets, and $M \sim 10^{-2} - 10^{-6} M_\odot$ for Jupiter-like ones.

Finally, in Fig. 3, we display the corrected total mass of the dark compact object as a function of the mass of DM for the strength parameter $y = 10^{-1}$ and for the neutron-star and white-dwarf branches. This figure is similar to Fig. 3 of Ref. [2], as the neutron star with 2 $M_\odot$ can not be obtained as the DM content reaches masses beyond $10^{-5} M_\odot$, one order of magnitude larger than the one obtained in Ref. [2]. A similar trend is obtained for the neutron-star branch in the strongly interacting DM case. Comparing this new figure with Fig. 3 of Ref. [2], in both cases there is still a more stringent limit in the DM content coming from the reduction of the nominal mass of a white dwarf of 1 $M_\odot$. However, the white-dwarf branch of the present figure shows a reduction of the nominal mass with decreasing DM content. This is due to the fact that we can have two different OM density profiles with the same DM content. A similar behavior is found for the white-dwarf branch for the strongly interacting DM case.

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