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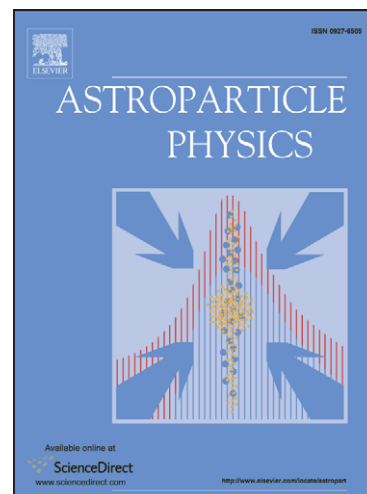
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Effects of mirror dark matter on neutron stars

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Abstract

If dark matter is made of mirror baryons, they are present in all gravitationally bound structures. Here we investigate some effects of mirror dark matter on neutron stars and discuss possible observational consequences. The general-relativistic hydrostatic equations are generalized to spherical objects with multiple fluids that interact by gravity. We use the minimal parity-symmetric extension of the standard model, which implies that the microphysics is the same in the two sectors. We find that the mass-radius relation is significantly modified in the presence of a few percent mirror baryons. This effect mimics that of other exotica, e.g., quark matter. In contrast to the common view that the neutron-star equilibrium sequence is unique, we show that it depends on the relative number of mirror baryons to ordinary baryons. It is therefore history dependent. The critical mass for core collapse, i.e., the process by which neutron stars are created, is modified in the presence of mirror baryons. We calculate the modified Chandrasekhar mass and fit it with a polynomial. A few percent mirror baryons is sufficient to lower the critical mass for core collapse by $\sim 0.1 M_{\odot}$. This could allow for the formation of extraordinary compact neutron stars with low mass.

Key words: neutron stars, dark matter theory

1. Introduction

Observations indicate that non-luminous matter contributes a significant part of the mass in galaxies. This “dark matter” (DM) cannot be made of known particles, but is of unknown type. In this paper we describe some po-

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tential effects of DM on neutron stars (NS), which can be tested with future observations of NS. These effects could be important also for the interpretation of the observational results. If DM exists, it should be present in all astrophysical objects, unless there is an efficient and unexpected segregation mechanism. DM can be present already in the formation processes and it can be accreted subsequently from the environment. Both of these processes should naturally occur, but the amount of DM that is trapped inside different objects should depend on the nature of the DM particles, the type of objects and their history. In general we expect that critical phases of stellar evolution could be modified in the presence of relatively small amounts of DM.

The most studied hypothesis is that DM is made of weakly interacting massive particles (WIMPs), which naturally appears in supersymmetric extensions of the standard model (SM) of particle physics. Should they exist, WIMPs accumulate in NS due to elastic scattering on nucleons. If the mass of accreted WIMPs reaches a critical value they become self-gravitating and form a dense core supported by degeneracy pressure. The dark core collapses into a black hole if it reaches the Chandrasekhar mass, $M \sim M_{Pl}^3/m_{DM}^2$. This limits the possible density, cross section and mass of WIMPs [1, 2]. See also [3]. The expected high mass of WIMPs gives a low Chandrasekhar mass for the DM core, they therefore do not affect the mass and radius of NS significantly. The annihilation of WIMPs in the DM core produces heat and old NS should therefore have a steady-state temperature of about 10^4 K [4]. The coldest observed NS have temperatures in the range $10^5 - 10^6$ K. It is observationally difficult to detect NS with significantly lower temperatures, because the luminosity scales as T^4 . The effects of WIMPs on NS therefore seems to be of little practical concern. WIMPs are, however, only one class of DM particles and some observations suggest that the model is oversimplified, see, e.g., [5] and references therein.

Mirror matter is another viable DM candidate that emerges if one, instead of (or in addition to) assuming a symmetry between bosons and fermions – supersymmetry, assumes that nature is parity symmetric. It is a matter of fact that the weak nuclear force is not parity symmetric. The main theoretical motivation for the mirror-matter hypothesis is that it constitutes the simplest way to restore parity symmetry in the physical laws of nature. When Lee and Yang proposed the non-parity of weak interactions in 1956, they mentioned also the possibility to restore parity by doubling the number of particles in the SM [6]. Thereby the Universe is divided into two sectors

with opposite handedness that interact mainly by gravity. In the minimal parity-symmetric extension of the SM [7, 8], the group structure is $G \otimes G$, where G is the gauge group of the SM. In this model the two sectors are described by the same lagrangians, but where ordinary particles have left-handed interactions, mirror particles have right-handed interactions. Except for gravity, mirror matter could interact with ordinary matter via so-called kinetic mixing of gauge bosons, or via unknown fields that carry both ordinary and mirror charges. If such interactions exist they must be weak and we therefore neglect them here. Since photons do not interact with mirror baryons, or interact only via the weak kinetic mixing, mirror matter constitute a natural candidate for the DM in the Universe. The study of the cosmological implications of mirror matter is well-defined, because the microphysics of mirror matter is the same as that of ordinary matter. Many consequences of mirror matter for particle physics and astrophysics have been studied during the last decades. The reader can refer to [9] for a review of the history of mirror matter and a list of most relevant papers published before 2006.

Like their ordinary counterparts, mirror baryons can form atoms, molecules and astrophysical objects such as planets, stars and globular clusters. However, even though the microphysics is the same in both sectors, the chemical content of the mirror sector should be different, because the cosmology must be different. In particular, Big Bang nucleosynthesis (BBN) requires that the mirror sector has lower temperature than the ordinary sector [10, 11]. This has implications for the thermodynamics of the early Universe [10, 12] and for the key cosmological epochs. Analytical results and numerical calculations of BBN [10, 13] show that the mirror sector should be helium dominated, and the abundance of heavy elements is expected to be higher than in the ordinary sector. Invisible stars made of mirror baryons are candidates for Massive Astrophysical Compact Halo Objects (MACHOs), which have been observed via microlensing events [14, 15, 16]. Mirror stars contain more helium and less hydrogen, and therefore have different properties than ordinary stars [17]. The consequences of mirror matter on primordial structure formation, the cosmic microwave background and the large-scale-structure distribution of matter have been studied [18, 19, 20, 21, 22, 23]. These studies provide stringent bounds on the mirror sector and prove that it is a viable candidate for DM. In addition, mirror DM is one of the few potential explanations for the recent DAMA/LIBRA annual modulation signal [24, 25, 26].

The properties of NS are intimately connected to the equation of state

(EoS) of matter at densities well beyond nuclear saturation density, $n_0 \sim 0.16 \text{ fm}^{-3}$. NS therefore are natural laboratories for the exploration of baryonic matter under extreme conditions, complementary to those created in terrestrial experiments with atomic nuclei and heavy-ion collisions. A stiff EoS at high density is needed to explain NS with high mass [27] and large R_∞ [28]. Heavy-ion collision data for kaon production and elliptic flow provide an upper limit on the stiffness of the EoS [29, 30]. By combining these constraints it is possible to test and exclude certain models of high-density EoS [31, 32]. In this context it is important to be aware of the potential effects of DM on the properties of NS. A long-debated question in compact-star physics is whether quark matter exist in the core of NS and whether there are unambiguous observables associated with that. Other exotic states of matter, e.g., meson condensates and hyperons could also exist in the core. For recent reviews, see [33, 34, 35]. For an example model of hybrid stars (stars with a quark-matter core enclosed in a nuclear-matter shell) that are consistent with present observational and experimental constraints, see [32]. A typical consequence of exotica is that the maximum NS mass and the radii of NS with typical masses, $M \sim 1.35 M_\odot$, becomes lower. Constraints on the mass and mass-radius relation of compact stars are therefore used as indicators for the presence/absence of exotica in compact stars. As an example, see the claim in [36] and the counter-examples provided in [37]. In this paper we show that if mirror matter (or, in principle, some other form of stable self-interacting DM) accumulates in NS, the equilibrium sequence could be significantly modified and the effect is similar to that of traditional exotic phases of matter. The NS equilibrium sequence is directly related to the ground-state equation of state and it is therefore commonly assumed to be unique. We show that if DM accumulates in NS this is not necessarily the case. See also [38], where potential effects of mirror matter on NS are discussed qualitatively.

2. Compact star sequence

The structure of NS with a mirror-matter part is determined by hydrostatic equations, which are similar to the well-known Oppenheimer-Volkoff (OV) equations. Here we repeat some essential steps in the derivation of the OV equations, and then we generalize the result to include mirror matter. The starting point is the line element, $d\tau^2 = g_{\mu\nu} dx^\mu dx^\nu$, of static isotropic

spacetime

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

and the energy-momentum tensor of a perfect fluid

$$T^{\mu\nu} = -pg^{\mu\nu} + (p + \rho)u^\mu u^\nu. \quad (2)$$

Here, p is the pressure and ρ the energy density, which includes rest-mass energy. The Einstein field equation simplifies to (units are chosen such that $G = c = 1$)

$$e^{-2\lambda(r)} = 1 - \frac{2M(r)}{r}, \quad (3)$$

$$\frac{d\nu}{dr} = \frac{[M(r) + 4\pi r^3 p(r)]}{r[r - 2M(r)]}, \quad (4)$$

$$\frac{dp}{dr} = -[p(r) + \rho(r)] \frac{d\nu}{dr}, \quad (5)$$

where

$$M(r) \equiv 4\pi \int_0^r d\tilde{r} \tilde{r}^2 \rho(\tilde{r}). \quad (6)$$

The metric should match the Schwarzschild solution at the surface of the star, which is located at $r = R$. It then follows from (3) that the gravitational mass of the star is $M = M(R)$. Similarly, the differential equation (4) for $\nu(r)$ is subject to the Schwarzschild boundary condition, so the integration constant is fixed. In combination with an EoS, $\rho = \rho(p)$, equation (5) determines how the pressure and density varies with r inside a star. Given an EoS and a central pressure, $p(r = 0)$, (4)-(6) are integrated until the surface is reached, where $p(r = R) = 0$. By varying the central pressure, a one-parameter sequence of equilibrium solutions with different M and R is obtained.

Newtonian physics applies to systems where rest-mass energy dominates. In general relativity, all forms of energy are sources of gravity. In particular, the curvature of spacetime inside a compact star depends not only on the energy-density distribution of matter, but also on the pressure, see (4). In the presence of mirror matter the metric is affected by the energy content in both sectors

$$p(r) = p_O(r) + p_M(r), \quad (7)$$

$$\rho(r) = \rho_O(r) + \rho_M(r). \quad (8)$$

Here, O (M) refers to the ordinary (mirror) sector. The metric functions, $\lambda(r)$ and $\nu(r)$, applies to both sectors and are given by (3)-(4) with the replacements (7)-(8). Equation (5) separates for the two sectors

$$\frac{dp_O}{dr} = -[p_O(r) + \rho_O(r)] \frac{d\nu}{dr}, \quad (9)$$

$$\frac{dp_M}{dr} = -[p_M(r) + \rho_M(r)] \frac{d\nu}{dr}, \quad (10)$$

because here we assume that particles and mirror particles interact by gravity only¹. This result can be generalized to any number of fluids that interact by gravity. In principle the two sectors could interact by other forces than gravity, e.g., by photon-mirror-photon kinetic coupling, which gives charged mirror particles an effective electric charge in the ordinary sector that is about eight or nine orders of magnitude lower than that of ordinary charged particles [39]. The effect of such eventual weak interactions on the equilibrium structure of a compact star should be small and we therefore consider only the gravitational interaction here.

Equations (4) and (6)–(10) are the general-relativistic hydrostatic equations for spherical stars with a mirror matter part. By choosing different central pressures in the two sectors, a star with different radius and baryon number in the two sectors is obtained. In Fig. 1 we plot compact star sequences with different number of baryons in the mirror and ordinary sectors. The EoS used here is based on a relativistic mean-field model of nuclear matter [40], which is combined with the Baym-Pethick-Sutherland (BPS) EoS for the crust [41]. In this work we approximate the EoS of mirror nuclear matter with that of ordinary nuclear matter, i.e., we use the same EoS in the two sectors. We motivate this approximation in the following way: NS are formed from the iron core of stars, i.e., of nuclei with maximum binding energy formed at the end of nuclear burning. They quickly become cold on

¹To understand this, consider the Newtonian hydrostatic equation, $\frac{dp}{dr} = -\rho_0(r) \frac{d\Phi}{dr}$, which tells that the gradient of the pressure is equal to the rest-mass density, ρ_0 , of fluid elements times the gradient of the gravitational potential, Φ . This is a classical force-balance equation. The gradient of the pressure in the mirror sector does not exert a direct force on fluid elements in the ordinary sector, and vice-versa, because here we assume that matter and mirror matter interact by gravity only. In the general-relativistic equation (5) the inertia of fluid elements is $p(r) + \rho(r)$ and $\nu(r)$ is the generalization of the gravitational potential. The separation of (5), with the replacements (7)-(8), into (9)-(10) follows because the two sectors interact by gravity only.

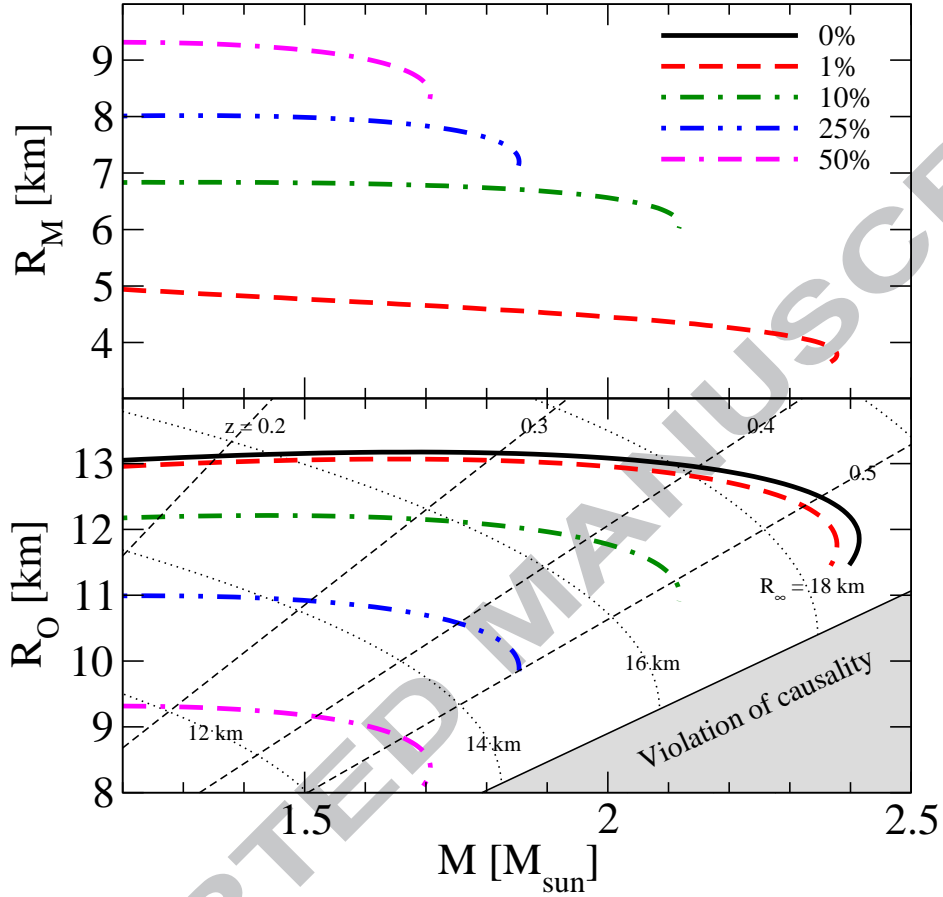


Figure 1: Neutron-star sequences for different number of baryons in the mirror sector, $N_M/(N_O + N_M) = 0\%$, 1% , 10% , 25% and 50% . Here, M is the total gravitational mass of the star and R_O (R_M) is the coordinate radius of the surface in the ordinary (mirror) sector. Here we consider $N_M \leq N_O$ only, but the results can be generalized to the opposite case by the replacement $R_O \leftrightarrow R_M$. These sequences correspond to a nuclear relativistic mean-field equation of state [40] and the crust is modeled with the BPS equation of state [41]. Included in the figure are also lines of constant surface redshift (thin dashed lines), $z = 1/\sqrt{1 - 2M/R} - 1$, and “radiation radius” (thin dotted lines), $R_\infty = R/\sqrt{1 - 2M/R}$. The latter quantity can be constrained via the surface emission from isolated neutron stars and is, in addition to the mass, an important indirect observable [28]. The surface redshift has not yet been reliably observed, but with future high-resolution observatories and a better understanding of neutron-star atmospheres this can become an important observable.

the nuclear energy scale, because of neutrino emission, and matter thereafter is in the ground state. The situation is different for the mirror-matter part of an NS. Different types of mirror nuclei can be accreted, e.g., from a binary companion mirror star, and an eventual mirror core of the progenitor star is not necessarily made of iron. The mirror core is, however, compressed into a compact object by the strong gravitational field of the NS. Mirror nuclei are therefore disintegrated into mirror neutrons, mirror protons and light mirror nuclear clusters, which should equilibrate with respect to weak nuclear reactions, just like neutrons and protons do in ordinary NS. In the minimal parity-symmetric extension of the SM (see the Introduction) the lagrangian of the mirror sector is identical to that of the ordinary sector. In this context it therefore seems reasonable to approximate the EoS of high-density mirror nuclear matter with that of ordinary nuclear matter.

The number of baryons in a star is the integral over the invariant volume element, $\sqrt{\det(g_{\mu\nu})}d^4x$, and the conserved baryon number current. The standard textbook result is

$$N_{O,M} = 4\pi \int_0^R dr r^2 n_{O,M}(r) \left[1 - \frac{2M(r)}{r} \right]^{-1/2}, \quad (11)$$

where n_O (n_M) is the number density of baryons (mirror baryons). The Schwarzschild boundary condition applies to the surface at $\max(R_O, R_M)$, because the local curvature of empty space in one sector is affected by the matter content in the other sector. The coordinate radius and the maximum mass of the sequence depend on the relative baryon number in the two sectors, see Fig. 2. In Fig. 3 we illustrate the density profiles of NS with identical number of ordinary baryons and different number of mirror baryons.

From these results it is clear that the mass-radius relation of NS is significantly modified in the presence of a few percent mirror baryons. The results presented in Fig. 2 can be generalized to $N_M > N_O$ by the replacement $M \leftrightarrow O$. It then follows that a mirror NS could be accompanied by a compact object in the ordinary sector that is only a few kilometers in size. Should they exist, such objects would have extraordinary properties, as the net gravitational mass is comparable to that of an ordinary NS. The relevance of these results in the mirror matter scenario depends on the probability for significant amounts of mirror baryons (baryons) to accumulate in the gravitational potential of (mirror) NS and their progenitor stars.

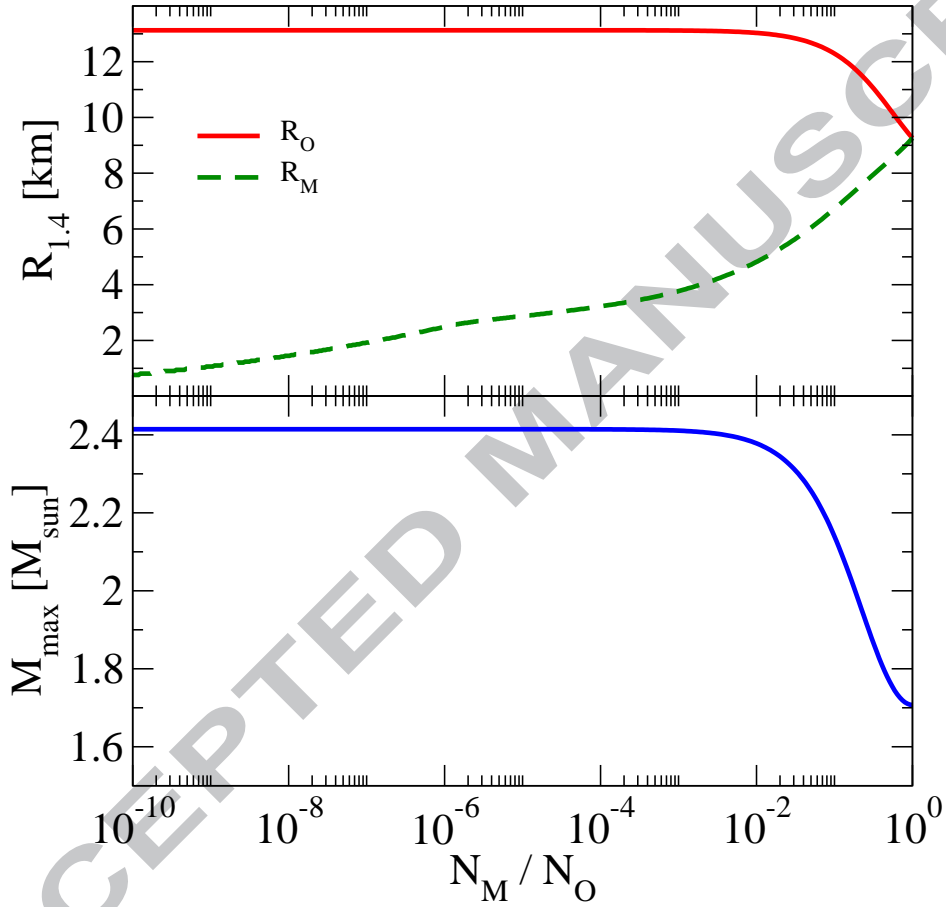


Figure 2: Radii of $1.4 M_{\odot}$ stars (upper panel) and maximum masses (lower panel) vs. the relative number of mirror baryons to ordinary baryons.

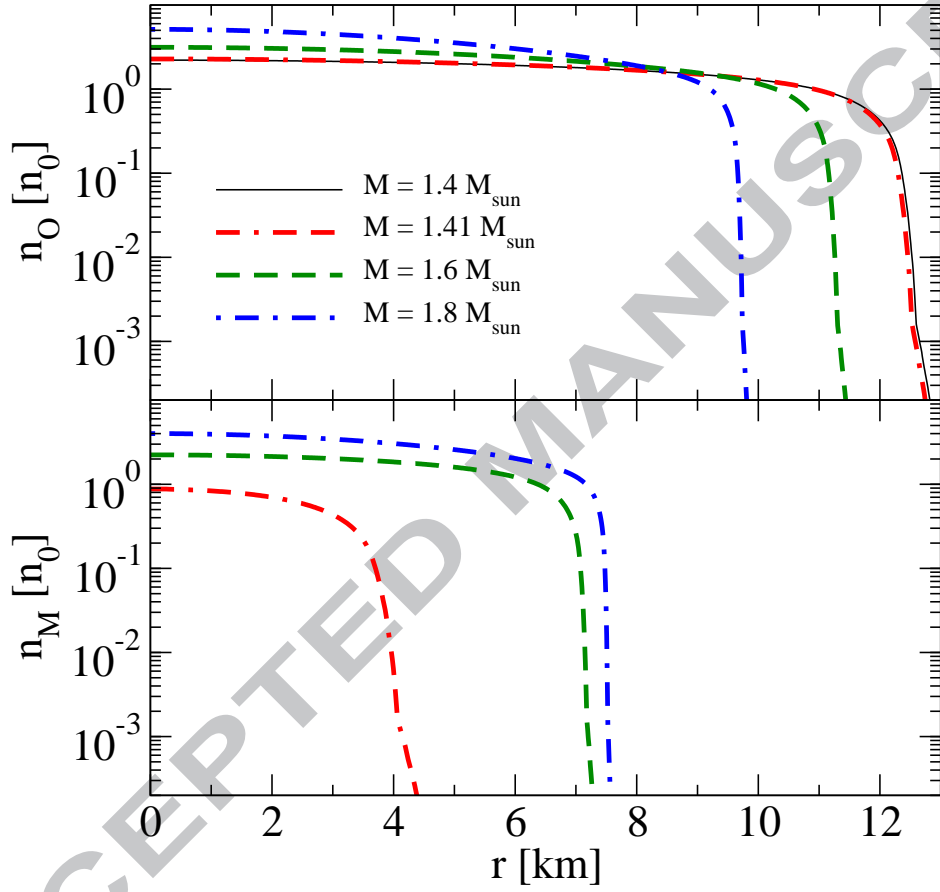


Figure 3: Density profiles of neutron stars with identical baryon number in the ordinary sector, but different number of mirror baryons. The number of ordinary baryons is fixed such that $M = 1.4 M_{\odot}$ in absence of mirror matter.

3. Core collapse and limiting mass

The critical mass of the core of ordinary stars is modified in the presence of mirror matter, because mirror particles act as an additional source of gravity. Such stars therefore collapse at lower core masses and this could result in extraordinary compact NS with low mass, due to the presence of mirror matter. In order to estimate the magnitude of the effect we modify the standard textbook calculation of the Chandrasekhar mass of a gravitating object supported by electron degeneracy pressure, see, e.g., [42] or [43]. We are interested in cores with high density that are near gravitational collapse. The density is essentially given by the rest-mass density of nucleons, ρ_0 , and the dominant contribution to the pressure, p , comes from ultrarelativistic electrons. The EoS is therefore approximately polytropic, $p = K\rho_0^\gamma$, with $\gamma = \frac{4}{3}$. The factor K depends on the relative number of electrons to nucleons and therefore depends on the chemical composition of the core. To leading order, this EoS and the hydrostatic equations give a limiting mass of

$$M_c \simeq 1.46M_\odot \left(\frac{Y_e}{0.5} \right)^2, \quad (12)$$

where $Y_e = n_e/n_B$ is the electron fraction, i.e., the relative number density of electrons to baryons. This is the traditional expression for the Chandrasekhar mass.

A self-consistent derivation of the limiting mass requires that the hydrostatic equations in the two sectors are coupled and solved simultaneously, as in Section 2. This is not trivial because the radial dependencies of the pressure and density are different in the two sectors. In order to obtain the critical mass as a function of the relative number of baryons in the two sectors we solve the hydrostatic equations, (4) and (6)–(10), with the polytropic EoS used in the derivation of the ordinary Chandrasekhar mass. The result is shown in Fig. 4. It is not necessary to account for general-relativistic effects in calculations of the structure of ordinary (and white-dwarf) stars, but since the equations are already presented in Section 2 we use them.

We limit the discussion here to the simplified situation when the electron fractions in the two sectors are equal. In this case the leading-order Y_e -dependence in the standard expression for the Chandrasekhar mass applies also to the situation when mirror baryons are present in the core, i.e., the numerical solution shown in Fig. 4 is proportional to $(Y_e/0.5)^2$. By fitting a

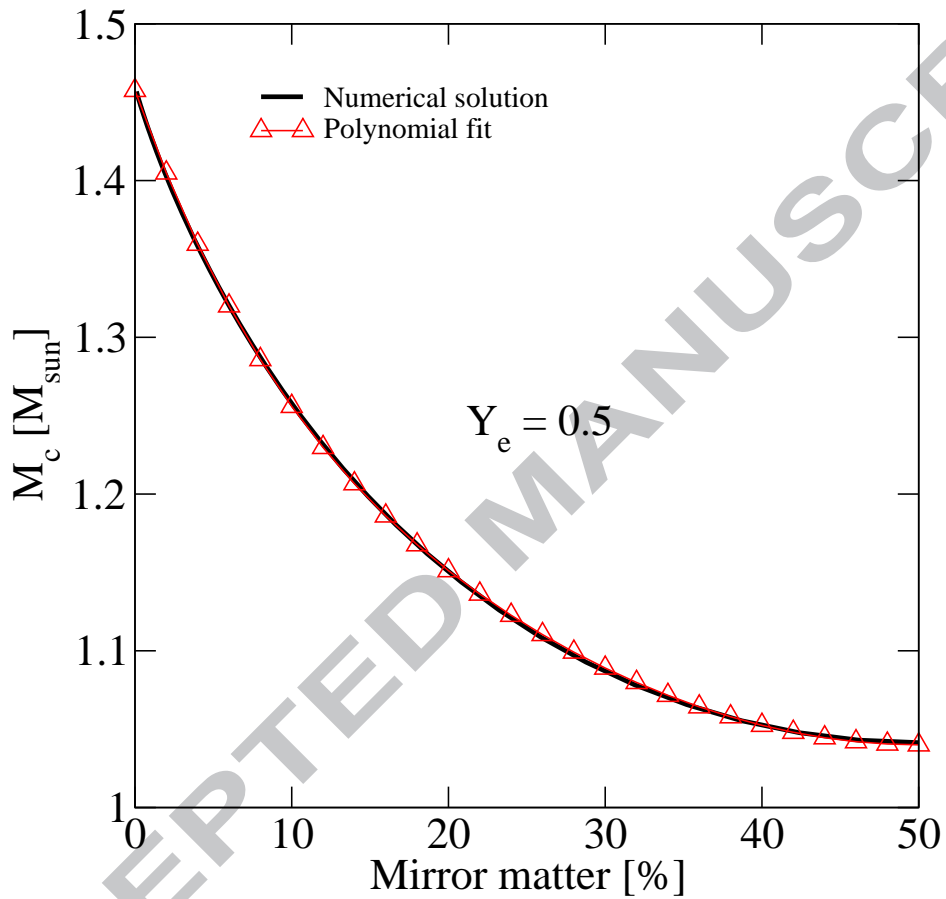


Figure 4: The modified Chandrasekhar mass vs. the relative number of baryons in the mirror sector, $N_M/(N_O + N_M)$, at fixed electron fraction, $Y_e = 0.5$. In the limit of 0% mirror baryons the traditional Chandrasekhar mass, $M_c \simeq 1.46 M_{\odot}$ is reproduced. The critical mass depends on the electron fraction, i.e., the chemical composition, which could be different in the two sectors. For equal electron fractions the Y_e -dependence of the model is simple, see (13).

polynomial to the numerical results we obtain an expression for the modified Chandrasekhar mass

$$M_c \simeq (1.04 + 1.26q^2 - 1.36q^4 + 12.0q^6) \left(\frac{Y_e}{0.5} \right)^2 M_\odot, \quad (13)$$

where $q = N_M/(N_O + N_M) - 0.5$ is the relative number of mirror baryons shifted by an offset of -50% that necessarily makes the solution even, because we use the same EoS in both sectors. The fit is shown in Fig. 4. In the limit of 0% mirror baryons the traditional Chandrasekhar mass, $M_c \simeq 1.46 M_\odot$ is reproduced. For 50% mirror matter our result is consistent with the estimate in [44]. The nature of the critical mass is somewhat different than the picture in this simplified model. In particular, the real cause of the collapse is the capture of energetic electrons by protons and a softening of the EoS in the core. The relativistic mass-limit considered here gives a qualitative picture of how the critical mass of the core is modified when mirror DM is present, or is accreted from the environment.

4. Accretion of mirror matter

The distribution of mirror DM in galaxies is expected to be non-homogeneous, because mirror baryons should form complex structures in a similar way as ordinary baryons do. There are essentially three different possibilities for the capture of mirror matter by an ordinary NS (the same would apply for the opposite situation, i.e., capture of ordinary matter by a mirror NS). First, NS should accrete particles from the mirror interstellar medium and this must not be in conflict with observations, e.g., by leading to gravitational collapse of young NS or too high surface temperatures vs. estimated ages. Secondly, the accretion rate could be significantly enhanced if an NS passes through a high-density region of space, e.g., a mirror molecular cloud or planetary nebula. The third possibility is that NS merge with macroscopic bodies in the mirror sector, causing violent events and possibly a collapse into a black hole. The probability of such events is low and should decrease with the mass of the dark objects, but they could be relatively easy to discover due to the high energy output, e.g., in the form of strange supernova-like events. One such observation has recently been reported [45]. We expect that the accretion rate increases towards the center of the galaxy and where the concentration of dark matter is high, e.g., in mirror stellar clusters. Therefore, the effects of mirror matter should depend on the location and history of each star. Note

that in general the local environment in the hidden sector is different from that in the visible sector. For example, an NS located in an empty galactic region could be surrounded by stars or a molecular cloud in the mirror sector. In fact, the structure formation process is different in the two sectors. Structures at small scales, like stars and stellar clusters, are formed essentially independently in the two sectors because they are electromagnetically decoupled. The process of accretion of mirror matter in ordinary stars were first studied by Blinnikov and Khlopov many years ago [46, 47].

The accretion rate of mirror matter depends on the location of the NS and the structure of the hidden mirror sector, which is unknown. We therefore limit the discussion here to some rough upper-bound estimates, which nevertheless leads to a useful conclusion. The accretion rate of mirror baryons can be estimated with the result for capture of collisionless particles in the gravitational potential of a compact object, Eq. (14.2.21) in [48]:

$$\dot{M} = \left(\frac{\rho_\infty}{10^{-24} \text{ g/cm}^3} \right) \left(\frac{10 \text{ km/s}}{v_\infty} \right) \left(\frac{M}{M_\odot} \right)^2 \text{ kg/s}. \quad (14)$$

Here ρ_∞ and v_∞ are, respectively, the density and speed of mirror particles. In the derivation of this expression it is assumed that the distribution of mirror particles is isotropic and monoenergetic at large distance from the NS. The quantities are normalized to the typical values for the interstellar medium in the ordinary sector of our galaxy. Giant molecular clouds made of ordinary baryons can be tens of parsecs in size and the particle number density can reach 10^6 cm^{-3} in some regions [49]. The clouds consist mainly of hydrogen ($\sim 70\%$) so the density can reach 10^{-18} g/cm^3 . If the density of the interstellar medium in the mirror sector reaches this value, an NS at that location would accrete about 10^6 kg/s . It is possible that mirror molecular clouds have higher density than their ordinary counterparts, because the mirror sector is subject to different initial conditions and should have different chemical composition. In particular, it is expected to be helium dominated. We account for these uncertainties by increasing the upper-limit estimate for the accretion rate from the mirror interstellar medium to 10^7 kg/s . We have checked that this limit remains valid also for NS with arbitrary high kick-velocities. In fact, the accretion rate is lower for NS with high speed. An accretion rate of 10^7 kg/s is, however, far too low to have a significant effect on the mass and structure of NS. Mirror matter must therefore originate from the progenitor star, or from a companion mirror star, if the effects on

the mass-radius relation discussed in Section 2 are to be observable. Note that the density considered above exceeds the average dark-halo density, which varies between about a tenth of a GeV/cm^3 to hundreds of GeV/cm^3 depending on the model used and the location in the galaxy. One GeV/cm^3 corresponds to about $10^{-24} \text{ g}/\text{cm}^3$, so on average the dark halo density is well below the $10^{-18} \text{ g}/\text{cm}^3$ that we consider in the estimate above.

The gravitational binding energy of NS is of the order of 10% of the mass-energy. While the accretion rate is too low to significantly affect the mass and structure of NS, one could imagine that the associated release of gravitational binding energy heats the star. The total binding energy can be calculated by comparing the energy of an NS in equilibrium before and after the accretion of a mirror baryon. The total mass-energy of a star is M (in units where $c = 1$) and the binding energy is $m_B N_B - M$, where M is the gravitational mass and m_B (N_B) is the baryon mass (net baryon number). The change of the binding energy when the mirror baryon number is increased by one is

$$\frac{\partial E_B}{\partial N_M} = \frac{\partial}{\partial N_M} \Big|_{N_O} (m_B N_B - M) = m_B - \frac{\partial M}{\partial N_M} \Big|_{N_O}. \quad (15)$$

This quantity is plotted with bold lines in the upper panel of Fig. 5 for three different choices of the baryon number in the ordinary sector. The EoS used is the same as that in Section 2. Most of this binding energy is released in the mirror sector. The kinetic energy of a mirror baryon that falls from great distance to the mirror-matter surface is $m_B [1 - \sqrt{g_{00}(R_M)}]$, where $g_{00}(R_M)$ is the time-component of the metric tensor at the surface. This kinetic energy is plotted with thin lines in the upper panel of Fig. 5 and it accounts for more than 97% of the total binding energy in all three cases. A significant part of the remaining small binding energy is accounted for by in-medium binding of the mirror baryon, i.e., m_B is higher than the energy per baryon in the medium. In principle there can be some heating of the ordinary part of the NS, e.g., due to weak interactions between the two sectors, but as we demonstrate below such effects are irrelevant from an observational point of view. See also [50], where this is discussed in some detail.

Isolated NS have essentially black-body spectra, so the net surface emission is given by the Stefan-Boltzmann law, $\dot{E} = 4\pi\sigma T^4 R^2$. The observed surface temperature of NS is around 10^6 K and the radius is of the order

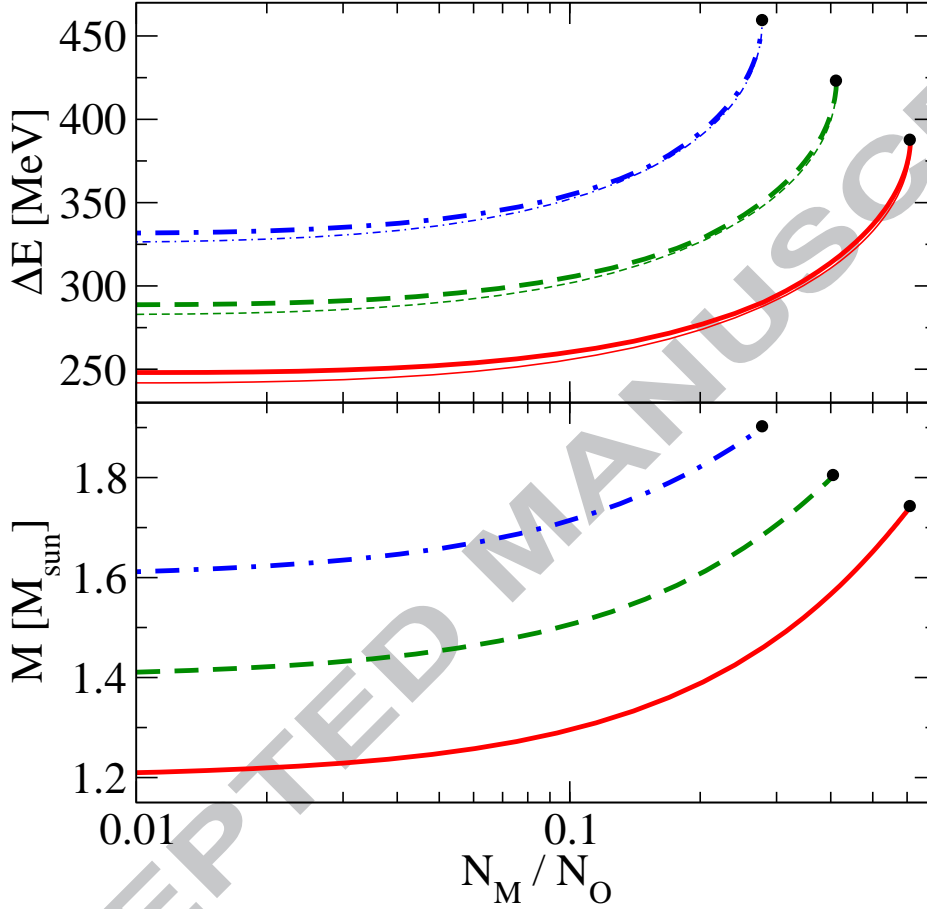


Figure 5: Change of binding energy per accreted mirror baryon (upper panel) and the total gravitational mass (lower panel) vs. the relative number of mirror baryons. The baryon number in the ordinary sector is fixed such that $M(N_M = 0) = 1.2, 1.4$ and $1.6 M_\odot$. Bold lines indicate the total change of binding energy (15), which includes both gravitational binding energy and nuclear binding energy. Thin lines indicate the kinetic energy of a mirror baryon that falls from great distance to the surface of the mirror-matter core, see text for further information. The solid disks indicate maximum-mass configurations, i.e., stars with higher mirror-baryon number are gravitationally unstable.

10 km, so the radiated energy is about 10^{25} J/s². If we assume that all binding energy is released as heat in the ordinary sector (this is clearly an overestimate), the upper-limit for the accretion rate, 10^7 kg/s, would correspond to a total heating effect of about 10^{23} J/s. The thermal emission from the coldest observed NS is about two orders of magnitude higher than this upper-limit estimate for the heating. Furthermore, most of the binding energy is converted to kinetic energy of mirror particles when they fall in the gravitational field. These particles will heat the mirror-matter core on impact, but that does not affect the temperature of ordinary matter, because the two sectors are electromagnetically decoupled. Consequently, the accretion of mirror matter in NS does not cause significant heating of the ordinary part of the star. The accretion-driven heating should be somewhat higher in the case of WIMPs, but the effect is presently not observable [4].

5. Conclusions

If DM is made of mirror baryons, they are present in all gravitational structures. In particular, they should exist in stars at the final stages of stellar evolution. In this paper we show that this could have significant effects on the formation and structure of NS. Our knowledge of NS is limited and highly dependent on observations. The situation is complicated by the fact that the conditions inside NS cannot be reproduced in laboratories. Ideally, we should learn how to calculate the ground-state EoS from first principles using the SM and then test it with observations of NS, but this task is presently too complicated. An intermediate goal is to unify “low-density” results from nuclear-physics experiments and lattice-QCD calculations with observed properties of NS. In that context it is important to understand the potential effects of DM on NS, so that the observations are not misunderstood and false conclusions about the microphysics are made. After all, DM apparently is dominant over ordinary matter and we do not know what it is. In this paper we illustrate that the NS sequence is significantly modified in the presence of a few percent mirror DM and the effect mimics that of other exotic forms of matter, e.g., quark matter. An observation of an extraordinary compact NS is therefore not sufficient to conclude that there must be

²Note that young neutron stars cool mainly by neutrino emission. The transition from neutrino-dominated cooling to photon-dominated cooling occurs at an age of about 100,000 years.

some form of exotic phase of ordinary matter in the star, since it can be explained also by the presence of mirror matter.

We find that the NS equilibrium sequence is a function of the mirror DM content, i.e., in contrast to the equilibrium sequence of ordinary NS it is not a one-parameter sequence. The maximum mass of the sequence and the radii of stars with typically observed masses, $M \sim 1.35 M_{\odot}$, decrease with increasing mirror baryon number. The *non-uniqueness* of the equilibrium sequence is the main result of this work, because it is not clear that it can be explained with traditional physics, nor with self-annihilating DM candidates such as supersymmetric particles. New measurements of NS masses and mass-radius relations are frequently made, thanks to the high resolution and sensitivity of modern observatories. The uniqueness property of the NS equilibrium sequence could therefore be put to the test in the near future. If it turns out that NS masses and radii cannot be explained with a one-parameter sequence (after effects of rotation are accounted for), one could search for a correlation between the orbits of the observed NS and the expected density of DM along those orbits. The accumulation of mirror matter in stars could have a significant effect also on the critical mass for core collapse. This is a potential formation mechanism for NS with low masses and extraordinary small size. These results can be used in future studies to test models of the mirror Universe.

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