# The Internal Structure of Neutron Stars from a New Perspective

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**Abstract:** This is a review article. Here we show that neutron stars, due to the atom-like structure of baryons and structure of spacetime, are mathematically very simple objects: they have an invariant density, a spherical shape although they spin very fast, they have no relativistic mass, and we can neglect the nuclear and gravitational binding energy. We also described mathematically the magnetars.

## 1. Introduction

The atom-like structure of baryons described in the Scale-Symmetric Theory (SST) causes that the neutron stars (NSs) are mathematically very simple objects.

According to the SST, baryons have an atom-like structure [1]. There is the core composed of the torus which interacts both electromagnetically and strongly, and there is the central condensate which interacts due to the nuclear weak interactions. Dynamics of the virtual objects shows that outside the core are created the orbits/tunnels in the SST Einstein spacetime which is composed of the neutrino-antineutrino pairs. Radii of such tunnels are defined by following formula

$$R_d = A + dB \,, \tag{1}$$

where $A = 0.6974425$ **fm** $\approx 0.7$ **fm** is the equatorial radius of the baryon core, $B = 0.5018395$ **fm** $\approx 0.5$ **fm**, and $d = 0, 1, 2, 4$. The $d = 4$ for the last tunnel/orbit is calculated from the range of the strong interaction which is generated by the torus in the baryon core.

The surface density of the torus is ~300,000 times higher than in the SST Einstein spacetime so moving baryons create ordered flows in the SST Einstein spacetime. It causes that angular velocities of both neutron star and the part of the Einstein spacetime it overlaps are the same. We can see that neutron stars which are spinning for an external observer are at rest in relation to the part of the Einstein spacetime they overlap, so they do not gain relativistic mass and are always spherical in shape. There is no need to use the framework of General Relativity for rotating neutron stars i.e. the stationary axisymmetric space-time metric [2].

## 2. Calculations

We claim that besides a very thin iron crust and very thin layer of nuclear plasma on surface of each neutron star (which we neglect in our calculations), the neutron lattice is composed of cubes with neutrons in their vertices (see Fig.1). Such neutron lattice is the very stable object because of the strong interactions between pairs of neutrons located at the ends of diagonals of the side walls of the cubes. The length of the diagonals is equal to the effective range, $R_{eff,NS}$, of the neutron matter. From (1) we obtain

$$R_{eff,NS} = R_{d=4} = 2.70480 \textbf{ fm} . \qquad (2)$$

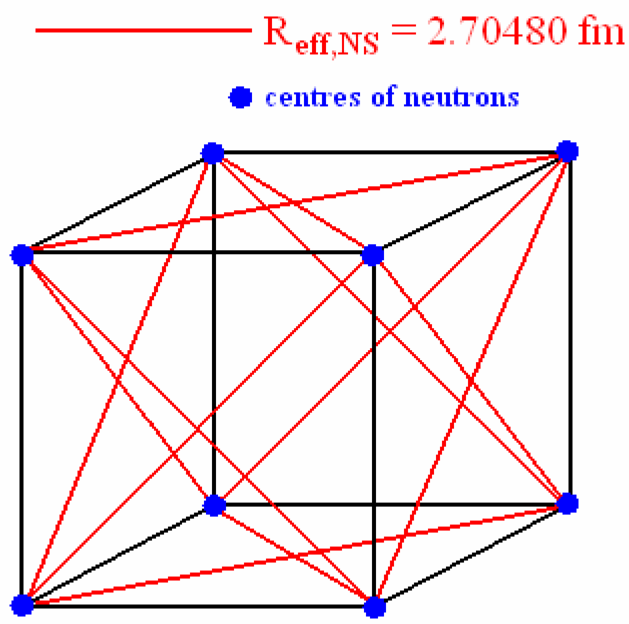


**Fig.1**
**Effective range of the neutron matter.**

This value is consistent with the mainstream value (~2.7 fm) [3] but due to the distribution of neutrons, we get a different density of neutron matter $\rho_{NS}$. Our value, contrary to the mainstream values, is invariant

$$\rho_{NS} = M_{Neutron} / (R_{eff,NS} / 2^{1/2})^3 = 2.39406 \cdot 10^{17} \textbf{ kg/m}^3 , \qquad (3)$$

where $M_{Neutron}$ = 939.565 MeV is the mass of neutron calculated in SST [1].

Why is the effective range $R_{eff,NS}$ equal to the length of the diagonal and not of the side of the cubes and why is it equal to the radius of the last tunnel for the strong interactions of baryons? For diagonals smaller than ~2.7 **fm** (from (1) we have that there can be ~1.7 fm, ~1.2 fm, or ~0.7 fm) the tori in the cores of baryons, which due to the very strong short-distance quantum entanglement cannot be disturbed or destroyed [1] (the half-integral spin and electric charge of such tori are conserved), would partially overlap, which, because of the very high surface density of the tori, is forbidden. Moreover, the binding energy of neutrons is higher for shorter distances so cubes with the side equal to 2.7048 fm are not in the ground state.

The upper limit for mass, $M_{NS,upper}$, and radius, $R_{NS,upper}$, of neutron stars we obtain from the boundary condition that spin speed on equator of NS should be equal to the speed of light in "vacuum" c = 299,792,458 **m/s**.

The below system of two equations leads to $R_{NS,upper}$ and $M_{NS,upper}$

$$R_{NS,upper} = G\, M_{NS,upper} / c^2 = 36.64 \textbf{ km} , \qquad (4)$$

where $G = 6.6740007$ **m$^3$ / (kg s$^2$)** is the gravitational constant calculated in SST [1],

$$M_{NS,upper} = \rho_{NS}\, 4\, \pi\, R_{NS,upper}^{3} / 3 = 24.81 \textbf{ solar masses}\,, \tag{5}$$

Such a biggest neutron star we call “the neutron black hole (NBH)” because it has the spin speed equal to $c$ on its equator.

The binding energy of neutrons in neutron stars that follows from the nuclear strong interactions, due to the very short time of interactions (~$10^{-23}$ s), is frozen inside the neutron star so there is no need to take it into account in calculations of NS mass.

But why can we also neglect the gravitational potential binding energy?

For example, let’s calculate the gravitational potential binding energy of a neutron, $\Delta E_g$, located at the surface of the neutron black hole

$$\Delta E_g = -G\, M_{NS,upper}\, M_{Neutron} / R_{NS,upper} = -M_{Neutron}\, c^2 = -939.565 \text{ MeV}\,. \tag{6}$$

This value suggests that such neutron behaves as a virtual neutron because the sum of its mass and binding energy is equal to zero. So, do we really have to consider the change in mass due to gravitational interaction? Well, no, and this is due to phenomena occurring in the SST Einstein spacetime.

When a star collapses into a neutron star or neutron stars collide, potential gravitational energy must be emitted, and this is due to the divergent flows in the SST Einstein’s spacetime, which the external observer observes as ripples in the spacetime. But due to the tremendous dynamic pressure in Einstein’s spacetime (~$5 \cdot 10^{44}$ Pa [1]), a reverse flow occurs that restores the initial state of local spacetime. Thus, it is the dynamic pressure in Einstein’s spacetime that means that we do not have to take into account the gravitational potential binding energy in the calculations of the mass of a neutron star.

We can say that the neutrons on the NBH surface are accompanied by virtual gravitational quanta of the potential binding energy with energy equal to the mass of the neutron, and such gravitational quanta are exchanged between the neutrons on the star’s surface. It is the gravitational quantum-star resonance! Such quanta are part of the zero-energy field.

The energy of virtual gravitational quanta on surfaces of NSs is not a linear function of the star’s mass but the mass of the star, $M_{NS,i}$, and the energy of the virtual gravitational quanta with the highest number density, $\Delta E_{g,i}$, should depend in the same way on the temperature of the star, so these two quantities are directly proportional to each other

$$\Delta E_{g,i} \sim M_{NS,i}\,. \tag{7}$$

From the boundary condition we have

$$M_{Neutron} \sim M_{NS,upper}\,. \tag{8}$$

From (7) and (8) we obtain the equation for the gravitational quantum-star resonance

$$M_{NS,i} / M_{NS,upper} = \Delta E_{g,i} / M_{Neutron}\,. \tag{9}$$

From (9), for $\Delta E_{g,i}$ equal to the characteristic masses for the atom-like structure of neutron, we obtain masses of NSs that behave in a strange way.

Using the formula (9), we calculated the lower limit for mass of NSs (0.891 **solar mass** – it relates to the characteristic energy of neutrinos in baryonic plasma $\Delta E_{g,i} = E_{Neutrino} = 33.74$ MeV [1]) and we described the gamma-ray bursts (GRBs).

We also showed that the interaction of our NSs with dark-matter (DM) loops leads to the conclusion that the TOV limit is an illusion [4].

The gravitational binding energy/mass of two neutrons, $\Delta M_{nn}$, in distance $R_{eff,NS}$ we can calculate from formula

$$\Delta E_g^{*} = -G\, M_{Neutron}^{2} / R_{eff,NS} = -\Delta M_{nn}\, c^{2}\,, \qquad (10)$$

so we have

$$\Delta M_{nn} \approx 7.70 \cdot 10^{-67}\ \mathbf{kg}\,. \qquad (11)$$

This value is close to the mass of the lightest non-rotating-spin neutrino-antineutrino pairs ($\sim 6.67 \cdot 10^{-67}$ **kg**) so between neutrons in NSs are exchanged the Einstein-spacetime components.

Colliding NSs with a total mass less or equal to 24.81 solar masses can merge into single neutron star, while NBHs cannot.

We should also remind that in SST neutrinos acquire their gravitational masses because they are immersed in the SST tachyon Higgs field and because gravitational fields are gradients created in the SST Higgs field by masses, so the “gravitational waves” detected by LIGO-Virgo are only indirectly related to gravitational fields.

### 3. The step changes in the *intrinsic* brightness of neutron stars as an undeniable proof of the correctness of the SST theory of NSs

In [1] we showed that the effective range $R_{eff,NS} = 2.70480$ **fm** relates to the virtual quanta with energy of $\Delta E_{g,i} = E_{eff,NS} = 187.573$ MeV. The virtual quanta appear in distance 2.70480 fm from centre of the neutron but their range is 4B = 2.00736 fm because they are created on the equator of the core of baryons [1].

Due to the quantum-star resonance, the *intrinsic* brightness of neutron star with a mass relating to $E_{eff,NS}$ should be significantly higher – from formula (9) we have

$$M_{NS,i=187.573} = M_{NS,upper}\, E_{eff,NS} / M_{Neutron} \approx 5.0\ \textbf{solar masses}\,. \qquad (12)$$

This result is consistent with the observational data [5].

In paper [4], we showed that for mass equal to 2.44 **solar masses** (the TOV limit) and higher, the *intrinsic* brightness should be significantly lower. On the other hand, for mass ~5.0 **solar masses**, the *intrinsic* brightness should be higher. It is not true that there is a mass gap for NSs with masses between the TOV limit and ~5.0 solar masses – for such an interval, the *intrinsic* brightness of NSs is much lower than a mean value so there is an illusion that the interval defines a mass gap.

For $E_{eff,NS} \approx 187.6$ MeV and $M_{NS,i=187.573} \approx 5.0$ **solar masses**, due to the quantum-star resonance, number density of the quanta with an energy of 187.6 MeV significantly increases – it looks as a LASER phenomenon. We should observe also some increases in *intrinsic* brightness of NSs for $\sim 2E_{eff,NS}$ and $\sim 4E_{eff,NS}$ [1], i.e. for masses ~10 and ~20 **solar masses**.

In SST, the diameter of the equators of the core of neutrons is equal to $D_{2A,NS} = 2A = 1.395$ **fm**. Ranges are inversely proportional to masses of virtual quanta so the $D_{2A,NS}$ relates to virtual energy equal to $\Delta E_{g,i} = E_{2A,NS} = 269.9$ MeV – this value is very close to mass of two neutral pions.

From (9) we obtain that the energy $E_{2A,NS}$ relates to mass of NS equal to

$$M_{NS,i=269.9} = M_{NS,upper} E_{2A,NS} / M_{Neutron} = 7.13 \textbf{ solar masses} . \tag{13}$$

For such NSs, *intrinsic* brightness should be also higher than a mean value so it leads to an illusion that abundance of NSs with such masses is higher – it also is consistent with the observational data [5].

The highest *intrinsic* brightness should be also for NSs with a mass of 1.395 **solar masses** (it relates to the mass of the central condensate in muons, $\Delta E_{g,i} = E_{52.83,NS} = 52.83$ MeV, which decays to electromagnetic quanta [1]) and for 1.78 **solar masses** (it relates to energy of the typical gluon loops: $\Delta E_{g,i} = E_{67.54,NS} = 67.54$ MeV [1]).

Let's summarize this chapter.

We obtained a series of masses of NSs with higher *intrinsic* brightness

$$M_{NS,i} \approx 1.395,\ 1.78,\ 5.0,\ 7.13,\ 10, \text{ and } 20 \textbf{ solar masses}, \tag{14}$$

but most important are following two threshold values: ~1.4 and ~5.0 **solar masses**.

A lower *intrinsic* brightness is for NSs with masses $M_{LIB}$ defined by the following interval

$$\sim 2.44 < M_{LIB} < \sim 5.0 \textbf{ [solar masses]} . \tag{15}$$

**4. Magnetars versus pulsars**

In paper [4], we showed that the spin-1 dark-matter loops have radius ~16.9 **km**. They are built of the spin-1 neutrino-antineutrino pairs with the spins tangent to the DM loop. Such a radius of neutron star leads to its mass equal to the TOV limit, i.e. 2.44 **solar masses**. The spin speed of the resting DM loops is equal to the speed of light in "vacuum" c.

We claim that magnetars are the neutron stars interacting weakly with the spin-1 DM loops i.e. the initial mass of magnetars should be close to the TOV limit: $M_{Magnetar} = 4.86 \cdot 10^{30}$ **kg**. Due to the weak interactions of the spin-1 DM loops with the nuclear-plasma vortex on surface of a magnetar, angular momentum of the vortex increases. We define the nuclear plasma as the plasma composed of 50% of protons and 50% of neutrons. Initially the weak interaction increases the spin speed of the nuclear-plasma vortex so there is created the very strong magnetic field, but as time goes on, the star's rotation slows down so the strong magnetic field weakens. Slowing the magnetar's rotation causes the radii of the DM loops to increase, separating them from the magnetar. Such increases in the radii of the DM loops combined with the weak interactions cause that the baryon matter is scattered so with time mass of the magnetar decreases.

Magnetic axis of magnetar has the same direction as the angular momentum of the DM loops. In neutron-stars, there can be an angle different from zero between the magnetic axis and the axis of rotation.

**Rotation of the free NSs is slowing down because of the friction between the rotating part of the Einstein spacetime inside the NSs and the non-rotating part outside them (the spin down).**

The friction in the Einstein spacetime together with strong magnetic field causes the emission of the polarized electromagnetic radiation.

The observed pulse periods of the so-called "normal pulsars" are between 0.3 s and 3 s. Assume that a pulsar with a mass of the TOV limit (so its radius is $R_{Magnetar} = 1.69 \cdot 10^4$ **m**) has the pulse period equal to $t = 1$ **s**. Then the spin speed of the nuclear-plasma vortex, $v_{Vortex}$ is

$$v_{Vortex} = 2\,\pi\,R_{Magnetar} / t = 1.06 \cdot 10^5 \text{ m/s} . \quad (16)$$

On the other hand, from [6] follows that the DM loops, due to their weak interactions with the condensates in centres of baryons, increase the spin speed of the nuclear-plasma vortex to $v_{Vortex\text{-}with\text{-}loops} = 5.8 \cdot 10^7$ **m/s**. It means that the DM loops increase the spin speed and decrease the vortex period, $t^*$, $N$ times

$$N = v_{Vortex\text{-}with\text{-}loops} / v_{Vortex} = 547 , \quad (17)$$

$$t^* = t / N = 1.83 \cdot 10^{-3} \text{ s} . \quad (18)$$

The Biot-Savart law relates magnetic fields to the currents. The magnetic field (magnetic flux density), $B$, at centre of a current loop (of the nuclear-plasma vortex) with a radius $R$ is

$$B = \mu_o\,Q / (2\,R\,t) , \quad (19)$$

where $t$ is the period (in magnetars it is the vortex period $t^*$), $\mu_o \approx 1.26 \cdot 10^{-6}$ **H/m** is the magnetic constant (the vacuum permeability), and $Q$ is the total charge of the loop/vortex.

From (19) results that magnetic field is inversely proportional to pulse period. Since the DM loops decrease the pulse period $N$ times so magnetic field of a magnetar with such a mass is $N$ times higher than the pulsar in the absence of the DM loops. We can see that magnetic fields of magnetars are indeed very strong.

The mass of the nuclear-plasma vortex, $M_{Plasma}$, should be as many times lower than the mass of the magnetar, $M_{Magnetar} = 4.86 \cdot 10^{30}$ **kg**, as the mass of the DM loop, $M_{DM\text{-}loop} = 2.0796 \cdot 10^{-47}$ **kg** [4], is lower than the mass of the neutron $M_{Neutron} = 1.6749 \cdot 10^{-27}$ **kg**

$$M_{Plasma} = M_{Magnetar}\,M_{DM\text{-}loop} / M_{Neutron} = 6.03 \cdot 10^{10} \text{ kg} . \quad (20)$$

It leads to the total electric charge, $Q$, of the nuclear-plasma vortex

$$Q = Q_{elementary}\,M_{Plasma} / (2\,M_{Nucleon}) = 2.89 \cdot 10^{18} \text{ C} , \quad (21)$$

where $Q_{elementary} = 1.6022 \cdot 10^{-19}$ **C** is the electric charge of proton, and $M_{Nucleon}$ is the mean mass of proton and neutron.

From the Biot-Savart law with the vortex period $t^*$, we have

$$B_{Magnetar} = \mu_o Q / (2 R_{Magnetar} t^*) \approx 6 \cdot 10^{10} \mathbf{T} . \quad (22)$$

This result is consistent with observational data because the magnetic field of magnetars is from $10^{10}$ to $10^{11}$ **T**.

From formulae (18), (17) and (16) follows that the initial period of the nuclear-plasma vortex $t^*$ in magnetar with the TOV-limit mass does not depend on initial period of pulsar

$$t^* = 2 \pi R_{Magnetar} / v_{Vortex\text{-}with\text{-}loops} = 1.83 \cdot 10^{-3} \mathbf{s} . \quad (23)$$

For such a magnetar, $Q$ and $R_{Magnetar}$ are the initially invariant values so the magnetic field equal to $\sim 6 \cdot 10^{10}$ **T** is the upper limit **unless there appears an accretion disc** (it increases magnetic field).

From [6] and formula (22) follows that the ratio of the magnetic field of the nuclear-plasma vortex, $B_{Nuclear}$, to the magnetic field of the vortex of electrons, $B_{Electron}$, is

$$B_{Nuclear} / B_{Electron} = t^*_{Electron} / t^*_{Nuclear} = (\alpha_{w(proton)} / \alpha_{w(electron\text{-}muon)})^{1/2} = 140.3 , \quad (24)$$

where $\alpha_{w(proton)} = 0.0187229$ is the coupling constant for the nuclear weak interactions, and $\alpha_{w(electron\text{-}muon)} = 0.951108 \cdot 10^{-6}$ is the coupling constant for the weak interactions of electrons [1], so we can neglect the $B_{Electron}$ in comparison with the $B_{Nuclear}$.

The composition of the nuclear-plasma vortex suggests that there dominates ionized helium-4. Radius of the ground-state orbit/shell in helium, $R_{Helium\text{-}4}$, has radius 4 times smaller than the Bohr first orbit in hydrogen

$$R_{Helium\text{-}4} = 0.529 \cdot 10^{-10} \mathbf{m} / 4 = 0.132 \cdot 10^{-10} \mathbf{m} . \quad (25)$$

From (23) results that $P \sim r_{Pulsar}$ is a relationship between the period, $P$, of a pulsar and its radius $r_{Pulsar}$. Assume that the first-time derivative of the period for pulsars, $dP/dt$ (it defines the changes over time in period of the pulsars) is defined by the ratio of the radius of the DM loops overlapping with the ground-state orbit in helium-4, $R_{Helium\text{-}4}$, to radius of the DM loops overlapping with the magnetic equator of the pulsar. For $r_{Pulsar} = R_{Magnetar} = 1.69 \cdot 10^4$ **m**, we obtain

$$(dP/dt)_{Pulsar} = R_{Helium\text{-}4} / R_{Magnetar} = 0.78 \cdot 10^{-15} \mathbf{s/s} . \quad (26)$$

From (26) follows that pulsars with smaller the equatorial radii have the first-time derivative of the period higher. Such values for pulsars are consistent with the observational data – see Figure 1 in [7].

In the pulsars, there is the friction between the rotating and non-rotating parts of the Einstein spacetime. But the friction in magnetars is much stronger because there appears also the very strong friction between the neutron star and the nuclear-plasma vortex. We can assume that the friction in pulsars leads to the electroweak interactions so there are produced the electron-neutrino pairs with energy equal to the mass distance between the charged and neutral pions: it is $\Delta E_{Pion} \approx 4.6$ MeV. On the other hand, the friction in magnetars leads to the nuclear strong interactions represented by the gluon loops with energy equal to $m_{LL} = 67.544$ MeV (it is close to a half of mass of the neutral pion) [1].

On the other hand, the Stefan-Boltzmann law is a function of total emitted energy of a black body $j^*$ proportional to its thermodynamic temperature $T$

$$j^* = \sigma T^4 . \qquad (27)$$

We can assume that $T$ is directly proportional to involved energy while the total emitted energy $j^*$ is directly proportional to the changes in period so we have

$$(dP/dt)_{Magnetar} / (dP/dt)_{Pulsar} = (m_{LL} / \Delta E_{Pion})^4 = 4.6 \cdot 10^4 . \qquad (28)$$

From (26) and (28) we obtain

$$(dP/dt)_{Magnetar} = 3.6 \cdot 10^{-11} \textbf{ s/s} . \qquad (29)$$

From (26) and (28) results that magnetars with smaller the equatorial radii have the first-time derivative of the period higher. Such values for magnetars are consistent with the observational data – see [8] and figure 1 in [7].

**Stronger interactions (here they follow from stronger friction) slow down rotation more effectively.**

Due to the strong friction in magnetars between the nuclear-plasma vortex and neutron star, the high temperature of the very thin iron crust below the vortex sometimes damages it almost simultaneously at two or more points, each with a diameter of several dozen metres. Through the damages, high-energy photons and neutrinos from beta decays are emitted. The damages are quickly repaired when the local pressure is reduced – such a mechanism produces millisecond pulses, and their time distance may be a second or so. The periods are defined by size and period of rotation of magnetars. Such a phenomenon was observed in magnetar SGR 1935+2154 [9]. The described phenomenon is a bit like volcanic eruptions at the junction of tectonic plates.

Due to an increase in density of dark energy, matter and energy tend to the state of uniform distribution. In turn, most of the interactions tend to create condensates. Gravity dominates on larger scales, but the appearance of the DM loops within baryonic plasma causes such plasma to disperse.

## 5. Summary

In this paper, based on the atom-like structure of baryons and structure of spacetime described in SST, we have expanded the physical side of the NS theory to show that the theory is complete. We showed also that in such a theory the key role play the dark-matter loops.

**Emphasize that due to the quantum-star resonance, higher *intrinsic* brightness of some NSs means also that their stability is higher so their abundances also should be higher.**

SST shows that General Relativity is neglecting some important phenomena in and around black holes so it leads to the wrong conclusions. Due to the formation of tunnels/orbits in spacetime as a result of the virtual strong interactions and the exchanges of the virtual quanta (especially the quanta with energy equal to 187.573 MeV), even the most massive neutron star (i.e. NBH) cannot collapse into black hole with a central singularity. According to SST, the massive black holes are built of the neutron black holes and neutron stars so they have an internal structure – their half-jets should be built of separated subjets. The dark-matter loops play a key role in the emission of hadrons and leptons by black holes. Black holes are not the mathematical black holes predicted by General Relativity.

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