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Cosmic Baby and Collective Motion-Formation of Sheet-Like Structure Inside the Magnetar Core: A Possibility

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Abstract: ***Ultra-strong magnetic fields ~ 10^{16} –10^{18} G (and even more i.e. 10^{19} G) and extreme pressure inside the core of a magnetar make its core as suitable for occurrence of extra-ordinary phase transition. Magnetic field decay in magnetar (i.e. neutron star) having relatively large surface dipole field > 3 x 10^{14} G and relatively young spin down age (~ 10^3 – 10^5 years) shows as strong evidence of magnetar with core that must have initial magnetic field > 10^{16} G (i.e. ~ 10^{17}G or more) and dipole field decay time scale ~ 10^3 years. An exotic inner core containing deconfined quarks, hyperons, strange quarks, etc. may exist in massive neutron star (i.e. magnetar). Under extreme pressure and density these quarks undergo their asymptotic freedom phase resulting which the core compactness reduces and quarks roam freely inside the core. Free quarks are affected in the presence of ultra-strong magnetic field in the interior of the core and due collective motion it is possible the ferromagnetic quarks first to form a "spindle" and finally re-shape into "sheet-like structure" at the center extending to outer core of the magnetar. This author proposes that the appearance of sheet-like structure might be possible inside the core of a magnetar (and neutron star also).***

Keywords: cosmic baby, Neutron Star

1. Introduction

In the deep sense "physics" actually means "knowledge of nature", i.e. involving the study of matter and its motion, behavior through space and time. This also provides the concept of energy and force as well as an endeavoring to understand the universe. The basic parameters of physics are the measurements of observable phenomena, finding the mechanism and the associated predictability of other events in nature.

Collective motion, the physical phenomena observed in nature, takes many forms such as schools of fish, flocks of birds, swarms of locusts, clusters of insects, etc. The important fact that commonly observed during the collective motion is that the individuals of the group avoid collisions. Thus, collective motion (CM) and the collision avoidance (CA)- these two behaviors provide as input which are processed by the individuals and finally defines "action" [1].

Collective motion (CM) can also occur in astrophysical compact objects individual (such as white dwarf, neutron star, black hole, etc.) and also in binary systems.

In this paper, I discuss the effects of collective motion on neutron star (i.e. in the form of cosmic baby i.e. magnetar *Swift* J1818.0 – 1607). In Sec.2 collective motion is discussed. In Sec.3 and Sec.4 compositions inside the core and possible magnetic particles in the core of a neutron star, respectively, are described. The possible strength of the magnetic fields in the neutron star core, estimated from the observations, are discussed in Sec.5 while effects of such ultra-strong magnetic fields on core matters has been expressed in Sec.6. The importance of recently detected cosmic baby i.e. Swift J1818.0 – 1607 in this context is described in Sec. 7. The time evolution of magnetar's super high magnetic field decay and heating the core are discussed in Sec.8. The possibility of sheet-like structure formation inside the neutron star core due to collective motion of quarks under ultra-strong magnetic fields are covered in Sec.9. Significance of sheet-like structure is mentioned in Sec.10 . In conclusion Sec. 11 it is proposed that sheet-like structure formation is possible at the center of a massive rotating neutron star under ultra-strong magnetic field.

2. Collective Motion

Any system, generally, consists of a large number of similar units (such as molecules, flocks of birds, etc.) such that
1) the interaction between the units can be simple (i.e. attraction or repulsion) or complex (i.e. combination of simple interactions), or
2) it can occur between neighbors in space, or
3) in an underlying network.

As a result, an appearance of transition can occur between neighbors in space or in an underlying network and ultimately the objects of the system adopt a pattern of behavior that indicates the collective effects of units in the system. The significant feature of this collective behavior is that an "Individual" units action is dominated by the "Other" implying that the unit behaves entirely different manner than from that of the way it would behave on its own. For example, a group of pigeons feeding grains spread on the ground. A random movement appears in the individual pigeon. But when a disturbance occurs then these pigeons leave the ground and move towards the sky making themselves as an orderly flying flock. This means individual non-ordered movements turn into an ordered scenario due to their collective motion. In other words, the details of the interaction between the units/ objects in a system are insensitive in this new equilibrium phase [2].

3. Composition of Neutron Star Core

The standard picture of neutron stars indicates-
i) the outer part of the neutron star, called the magnetosphere, consists of partially ionized atoms and electrons, mass densities below about 10^4 g.cm $^{-3}$. At higher densities i.e. > 10^4 g.cm^{-3} the spatial region consists of inhomogeneous nucleonic matter and electrons called the crust. This crust is divided into two: (a) an outer crust with a plasma of nuclei and electrons a degree of freedom, and (b) an inner crust where unbound neutrons exist [3].

ii) The outer crust: It is composed of completely ionized nuclei in the sea of electrons almost constant density (arise due to incompressibility of the highly degenerate electron fluid). At densities of ~ 10^7 g.cm^{-3} and below a crystal form of ^{56}Fe nuclei is expected [4]. Theoretical studies [5, 6] suggested that heavy clusters of matter with exotic shapes, i.e. "Pasta phases", could arise in the bottom part of the inner crust. Numerical studies [7,8] suggest that the transition densities between the different geometries and the crust core transition are affected by very strong magnetic field (B)≈ 10^{18} G.

iii) Core- In 1972 Ruderman [7] first suggested the possible nuclear matter in neutron star interior may have anisotropic features at very high densities ~ 10^{15} g.cm^{-3}. These anisotropic features may be a mixture of different types of fluid, superfluid or magnetic fluids. Our present understanding indicates that the core is divided into three- i) the outer core ii) the inner core and iii) the center. The neutron star core contains superfluid neutron degenerate matter that mostly composed of neutrons (90%) and as a small percentage of protons and neutrons (10%) [8,9]. Many exotic forms of matter such as freely roaming quarks, gluons [10] may also present. Even, under the extreme conditions, i.e. gravitational pressure, the interior neutrons will deformed and turn into de-confined quarks, hyperons, strange quarks [11]. Note that the contraction continues due extreme pressure and density which push the quarks into their asymptotic phase (i.e. strong forces among quarks almost vanish) resulting which core compactness vanishes, quarks roam freely. This means that the cores of massive neutron stars contain a large number of quarks (u….u, d….d, s…s i.e. multi-quarks droplets and be stable [12]. This situation is different from that for droplets of strange quark matter containing approximately the same amount of u-, d-, and s- quarks. For this reason, Annala et al [13] showed the presence of quark matter core in the interior of the maximally massive stable neutron star. According to their estimation a quark core of approx.. 6.5 km is possible in the massive core of neutron star with mass M >~2 $M_\odot$ and radius (R) ~ 12 km.

4. Magnetic particles inside the neutron star core

In neutron star its core or central density is few times more than the surface density and it is expected that quarks are to be de-confined inside the core. It is called quark matter and possibly the neutron star entirely made of quark matter. This means that the neutron star whose core is made of quark matter can be regarded as a hybrid star. The known fact is that most of the neutron stars have strong magnetic fields. Thus, quarks and leptons have anomalous magnetic moment (AMM) and provide response against very strong magnetic fields [14]. Not only that strange quark matter is self-bound, so strange quark matter could be found in the core of neutron star. The significant role of these strange quark matter is that these astrophysical objects' (i.e. neutron stars, strange quark stars) strong magnetic fields affect the microscopic properties of matter that ultimately modify the macroscopic properties of the system.

5. Strong magnetic fields inside the neutron star core

The compact stars, such as neutron stars, magnetars (isolated neutron star with strong magnetic field) possess very strong magnetic field. The typical values of the surface magnetic field (inferred from magnetic dipole model and spin down rates) are in the range of 10^8 – 10^{13} G [15] whereas inferred periods of anomalous x-ray pulsars (AXPs) and soft gamma repeaters (SGRs) suggest that neutron stars have larger surface magnetic field ranging 10^{14} – 10^{15} G [16] and even may be further more i.e. 10^{16} – 10^{17} G [17,18]. On the other hand, numerical simulation and theoretical studies argued that at the center of inhomogeneous, ultra-dense, gravitationally bound compact stars such as neutron stars, magnetars may have magnetic fields ~ 10^{19} – 10^{20} G [19,20].

6. Effects of strong magnetic fields and structure formation

6.1 Observational evidence of formation of 'spindle' and 'flotilla' due collective motion

Baun et al [21] performed their experiment considering the first motion of the magnetic particles (i.e. super-paramagnetic particles) suspended at the water air interface and then applied a magnet system which provides a strong homogeneous, dipolar magnetic field (B_o) to magnetize and orient the super-paramagnetic particles and then a second quadrupolar field (which is with a specially constant tensor ΔB and superimposed on the first) to generate a magnetic force on the oriented particles. Their significant observations were:

1) The used magnetized micron-sized particles are driven by applied quadrupole magnetic field that induce the formation of densely packed strings (or chain) of magnetic particles, then
2) After reaching a certain length, the particles or small particle chains can attach towards the center of the string and form a "spindles"; and
3) Finally, string and spindles can form a large assemblies as "flotilla".
4) This flotilla moves as a whole depending on the applied field gradient with a velocity 'U '(i.e. the velocity is anisotropic with components $U_{\parallel}$ and $U_{\perp}$) (see figure 1 of reference Baun et al [21]).

6.2 Effect of strange quark matter in strong magnetic field

In a study of searching the effect of strange quark matter with strong magnetic field inside the core of neutron star Gonzalez-Felipe et al [22] investigated first the microscopic properties of strange quark matter under strong magnetic field and then modified that results into the possible macroscopic properties of that system. Taking into account the β-equilibrium and charge neutrality they found strange quark and electrons response (i.e. interact) with the magnetic field via their electric charges and anomalous magnetic moment (AMM) . The significant findings of their study are:

1) In strange quark matter the contributions from the AMM of the quarks is significant whereas the effects of the AMM for electrons is small in neutron star's magnetic field 10^{15} –10^{19} G.
2) There exist an upper limit for magnetic field i.e. 8.6 x 10^{17}G for the stability of the system consisting of strange quark matter (SQM) with electrons, beyond which no quark star exists.
3) For the magnetic field strength ~ 10^{19} G quark matter undergoes a phase transition implying that the stability conditions of SQM is modified in the presence of a strong magnetic field. In other words, a phase transition in a SQM system could be hidden for the field > 8.6 x 10^{17} G two situation arise:
   a) if strange quark star exist then they can not support magnetic fields greater that 10^{18} G (i.e., > 10^{18} G) ;
   b) in the case of SQM the ferromagnetic phase transition due to AMM would be guaranteed (i.e. acertain) for magnetic fields of ~ 10^{18} G.

6.3 Study of structure formation of magnetic particles through numerical simulation

In order to understand the properties of the randomly dispersed ferromagnetic particles under strong magnetic fields Ando etal [23] performed a numerical study using the particle composites which are not magnetic field structured. In fact, when a strong magnetic field is applied to the magnetic particles (i.e. Ni) which are dispersed in medium, their significant observations were:

1) A chain like cluster is formed by magnetic particles along the parallel direction to the applied field.
2) The structure formed by the magnetic particles is independent of particle diameter but dependent on the particle volume concentration. In particular —
   a) for particle volume concentration (φ) = 5 vol %- no bundle of chain-like cluster is formed;
   b) for particle volume concentration (φ) = more than 10 vol. %- the bundle structure is found via contacts of multiple chain-like clusters and this process continues.

7. Why Cosmic baby is so important?

Basically, Magnetars are a sub-nuclear of isolated neutron stars with large surface magnetic fields ~ 10^{14} – 10^{15} G. Till date 31 magnetars have been detected. Only a few i.e. 6 magnetars have characteristic age less than 1000 years and rest have more than thousands years [24,25]. Among these six magnetars the recently detected magnetar i.e., *Swift* J1818.0 – 1607 is the youngest magnetar having characteristic age ~240 – 300 years at the time of discovery in the year 2020 [26,27]. This *Swift* J1818.0 – 1607 is known as "Cosmic Baby" due to its baby phase (in comparison to thousands years). Various early observed / estimated parameters of this cosmic baby are [26 – 28]:

Coherent periodicity of X-ray signal ~ 1.36 s
Period derivative ~ 9 x 10^{-11} s.s^{-1}
Spin Period = 0.7333920 s
Spin period derivative = 8.2 x 10^{-11} s.s^{-1}
Luminosity ~ 8 x 10^{34} erg.s^{-1}
Surface magnetic field ~ 2.7 x 10^{14} G

Dipole Magnetic field at poles ≈ 7 x 10^{14} G
Characteristic age (shortest known) ~ 240 years.

Considering the ambipolar diffusion which is active to present both the decay of interior magnetic fields and cooling the neutron star i.e. magnetar (as the effect is same and applicable for magnetars as well as neutron stars also) Parui [29] showed for this cosmic baby that

a) It's core temperature will stay higher than several times 10^8 K for a period of few thousand years (at least 10^3 years) ;
b) core interior magnetic field strength = 8.9424 x 10^{17} G ;
c) ellipticity of this new born magnetar is ~ 9 x 10^{-3} and estimated possible duration of trriaxiality suggests that the cosmic baby will exhibit its triaxial nature for at least 700 – 760 years.

This means that various effects of ultra-strong magnetic fields, phase transitions on the core material of this baby magnetar will occur for long duration which is a golden opportunity to the astronomers for their continuous watching through the observation of the "group up" of the compact object. Not only that, this cosmic baby plays an important role that can be analyzed in two folds, i.e. one way as a young magnetar while the other way as a triaxial star.

7.1 Ferromagnetism in quark matter inside the magnetar core

With the analogy of the energy scales for the systems between the electron system (e^-) and quark system (q) Tatsumi [31] found, in his study towards investigating the origin of magnetic field, the strength of the magnetic field generated due to magnetic interaction of electrons (i.e., electron system) is (B) = 10^{15} G while for quark system the magnetic field strength is less than that of the electron system depending on the quark mass. They have also found ferromagnetic instability which is feasible for both in massive quark system and in low quark system. This implies that if a ferromagnetic quark liquid exists either stably or meta-stability around or above the nuclear saturation density then

1) Strange stars may have a strong magnetic field;
2) The strength of this magnetic field is so high that is enough to magnetar [32]; i.e.
3) This can be applicable for strange quark star as magnetar modeling of SGR or AXP;
4) This ferromagnetic properties of quark matter can also provide a source for origin of magnetic field (~ 10^{15} – 10^{17} G) in compact stars [33].

8. Time evolution and magnetic field decay of magnetar

The moment, when a neutron star is born, is obscured by dense stellar material, thus immediate properties of newly born neutron stars are impossible to measure. By analyzing the sample of young neutron stars associated to supernovas (as an alternate) it is only possible to constraint the initial properties of neutron stars [34]. Because these remnants stay bright and structured up to≈ 30 kyr age, relatively easier to find in radio and /or x-ray observations [35]. Out present knowledge of the initial properties oneutron stars is that newly born strongly magnetized neutron stars (i.e., magnetars) have

1) Magnetic fields strength (B) ~ 10^{14} – 10^{15} G [16, 36 – 38];
2) Fast rotation period ~ few msec; and
3) Could be responsible for GRB after glow [39,40];
4) These magnetars are considered as central engine for at least one FRB; as well as
5) High energy burst source from galaxy also [41].

Considering the 56 neutron star samples (selected from ATNF Catalog) that are uniquickly associated with supernova remnants (SNRs) Igoshev et al [42] studied the distribution over the initial periods and magnetic fields of these young neutron stars i.e. radio pulsars, magnetars and found distribution for magnetic fields successfully matching with the log-normal distribution of initial parameters i.e., period P_o≈ 0.09 s with 68%confidence interval. But for magnetars the period distribution (including the initial periods) indicates slightly to be distinct from the period distribution of isolated radio-pulsars, showing the concentration of magnetic period at P_o > 2 s. This implies that

1) The distribution of magnetic fields and periods for radio-pulsars are both well described in the log-normal distribution scale.
2) For magnetars, the average magnetic field does not evolve significantly with time in the logarithmic scale.

According to the standard theory a newly born neutron star (i.e.a proto-neutron star) is born as extremely hot and liquid with temperature T >~ 10^{10} K and a relatively large radius R ~ 100 km. It becomes transparent to neutrinos within a minute and as a result, shrinks to its final size R ~ 12 km [43,44]. The draining of energy due to escape of the thermal neutrinos from neutron star core makes a further temperature drop by another order of magnitude to T ~10^9 K [45] within a few minutes. In the case of rotating neutron star r-mode arises due to coriolis force (with +ve feedback) [46,47]. The growth of this r-modes can be suppressed due to the action of viscous damping and some non-linear effects. This r-mode instability, thus, can lead to

1) Stellar differential rotation that ultimately determines a saturation state of the instability [48,49] ;
2) Formation of a toroidal magnetic field component which is amplified by winding up the seed poloidal field (~10^{11} G) in the core of neutron star [50,51] and can be able to generate an ultra-strong (~ 10^{17} G) toroidal field component [52] ; and
3) With the increase of toroidal field in a stable, stratified stellar interior, Taylor instability appears that makes the toroidal fielde to be partly transformed into a new poloidal component. Thus, new formation of stable poloidal – toroidal twisted torus configuration in the neutron star core.

According to Cheng and Yu [52] a newly born neutron star with rapid rotation and under such above mentioned situation could

1) Becomes a magnetar within a time scale of 10^{2-3} s
2) With a surface dipolar magnetic field and
3) Spin down to a period of ~ 5 ms because of gravitational wave radiation due r-mode instability as well as non-axisymmetric stellar deformation caused by transformed toroidal field.
4) The r-mode instability ends (as per simulation result) at stellar temperature around 5.5 x 10^9 K.

This implies that under the dynamo process, as mentioned above, it is possible for a neutron star that could turn into a magnetar with surface dipole magnetic field strength of ~ 10^{15} G on a time scale ~ 10^2 – 10^3 seconds.

Assuming a magnetar as a common neutron star having a total mass of M = 1.4$M_\odot$ and its radius = 10^6 cm Gao et al [60] studied the super high magnetic field decay of magnetars associated with supernova remnants. The significant results, according to their calculation, are:

1) Initial internal magnetic field of the common magnetars B_o = 3.0 x 10^{15} G and initial temperature T_o = 2.6 x 10^8 K.
2) The evolving (i.e. decay) time scale of the super-high magnetic fields may be in the range ~ (10^6 – 10^7) years for common magnetars but the maximum time scale of the field decay t = 2.9507 x 10^6 years.
3) After the evolution, the maximum magnetic field of the magnetar progenitor B_{max} = (2 x 10^{14} – 2.93 x 10^{15}) G when temperature T_o = 2.6 x 10^8 K and B_{max} = (10^{14} – 1015) G at T_o ~ (2.75 – 1.75) x 108 K.

This means that after the evolution of magnetic field decay for a period of ~ 3 x 10^6 years, the maximum magnetic field strength of the magnetar still remains high which is in the range that of possessed by a normal magnetar. It is to be noted that ages of the considered all the supernova remnants are not more than 10,000 years i.e. the considered supernova associated magnetars are much younger in comparison to common radio-pulsars.

Regarding the evolution (i.e. decay) of super-high magnetic fields inside the magnetars various models have been proposed like twisted magnetosphere model, unwinding of the internal field shears the star's crust model, rotational crustal motion model, etc. The most effective model is the thermal evolution model. In this model high magnetic field of magnetar could decay directly as a result of the non-zero resistivity of the internal matter through Ohmic decay or Ambipolar diffusion [53] or indirectly due Hall drift production [54,55]. The basics are: the magnetic field decay is treated as main source of internal heating that ultimately contributes in rising the magnetar surface temperature. In this model, the surface thermal temperature of a magnetar is estimated to be ~ (10^5 – 10^6) K as per consistent with the observations [56,57] and the possible magnetic field

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evolutionary time-scale is calculated as t ~ (10^6 – 10^7) years based on the statistical distribution of observed normal radio-pulsars in the (P – Ṗ) diagram [58,59].

A study , performed by Dall'Osso et al.[61], of magnetic field decay in neutron star by accounting large rotation period with relatively large surface dipole field strength (B_{dipole} > 3 x 10^{14} G) and relatively young spin down ages (τ_c ~ 10^3 – 10^5 years) indicates strong evidences of dipole field decay on a time scale of ~ 10^3 years in case of compact objects (i.e. neutron star, magnetar) having the strongest dipole field B_{dipole} ~ 10^{15} G. This decaying field indicates

a) The compact object (i.e. neutron star, magnetar) is a younger age one than the age calculated by using (P / 2Ṗ) , and
b) The strength of the internal magnetic field decay must have larger initial value > 10^{16} G i.e. may be ~10^{17} G or even more.

Recent numerical simulation study [62] by considering the combined of these three processes — Ambipolar diffusion, Ohmic dissipation and the Hall drift , precisely the simultaneous evolution of the magnetic field in the crust due to Hall drift and Ohmic dissipation and in the core due to Ambipolar diffusion, indicates that the rate of conversion of magnetic field energy into heat inside the core by the Ambipolar diffusion is more than that of in the crust by Ohmic dissipation and Hall effect i.e., enhancement of the magnetic field decay in neutron star, magnetar. This implies that Ambipolar diffusion pocess plays an important role such that this process can prevent the cooling of the magnetar core below a temperature of 10^9 K.

9. Possible sheet-like structure formation inside magnetar core

Regarding the constituents inside the core of a neutron star (see Sec.3) it is expected that the matter contains nucleons, electrons, and other particles such as muons, pions, kaons and their condensates, hyperons, strange quark matters (i.e., large number of quarks, so called multi-quark droplets) [63]. In fact, this stable quark matter may exist even without gravity [64,65]. Not only that, due to high enough density inside the core, the degrees of freedom i.e., the freely three quarks - "u", "d", and "s" quarks may appear, showing ferromagnetic phase transition as ferromagnetic liquid.

Regarding the strong magnetic fields of neutron star, as inferred from AXPs [66], the typical magnetic field strength on the surface of (a) a pulsar is ~ 10^{12} G, and (b) magnetar ~ 10^{13}- 10^{15}G, and in the interior of a magnetars the magnetic field strength can reach 10^{16} – 10^{18} G [67,68] and even large values of about 10^{19} – 10^{20} G [36]. In this context, Dvornikov [69] predicted the possible amplification of the seed magnetic field 10^{12} G in neutron star core (driven by the electroweak interaction of quarks) that

1) Generates such strong magnetic field in dense quark matter; and
2) The generated strong magnetic fields can affect the shape, mass and radius of neutron stars, magnetars (i.e. compact objects).

This implies that the geometry of the interior magnetic field is at least as important as the field strength itself on the structure formation inside the neutron star core. Note that study of strong magnetic field [70] indicates that a tangled, isotropic magnetic field has a relatively smaller impact on neutron star's mass, radius and the core. As a result, the ferromagnetic liquid, the strange quark matter (i.e., magnetized ferromagnetic quark particles) of the core form clusters inside the neutron star core in the presence of strong magnetic field after magnetically attracted into aggregating.

From the observational analysis it is known that neutron star dipole magnetic field axis is not aligned with its rotational axis and its rotation or spin period is only a fraction of a second. Thus, high frequency rotation and ultra-strong magnetic field both might be active on its core and affect the core material into structure formation. This means that in the presence of ultra-strong magnetic field large number of quark clusters turn into chains that ultimately deformed and finally re-shape into sheet-like structure inside the core system. These newly form sheets extend inside the whole core i.e. from the center to the outer core of the neutron star.

10. Significance of the sheet-like structure in Magnetars

After the discovery of neutron star in the form of pulsar in 1967 the main idea was that neutron star is made up primarily of neutrons along with small amount of protons and electrons. "What is inside the core" was totally unknown. In 1973 Canuto and Chitre [71] first gave theoretical idea that neutron star core may be a solid core. At the same time, using modified Brueckner theory Mittet and Østgaard [72] suggested that the possible phase transition turns the normal neutron matter into more compact matter i.e. "neutron solid" under extreme conditions. Various theoretical studies suggested that superfludity and superconductivity aided properties are also present in the core material of the magnetar. This sheetlike structure idea adds a further extended form of solid inside the core of a magnetar.

11. Conclusion

Neutron star core means the presence of ferromagnetic liquid, multi-quark droplets as if a composite form available in strange quark matter. The seed magnetic field of strength ~ 10^{12}G, present inside the core, is amplified to generate strong and ultra-strong magnetic field in the interior of the neutron star. Due to rotation the whole interior system of the neutron star rotates with the same frequency of stellar rotation. As an effect of star's rotational effect the internal core materials, which are already in the form of chain, are deformed and ultimately re-shaped into sheet like structure. This means that sheet-like structure formation appears in the interior strange quark matter of the core of the rotating massive neutron star ((in the case of magnetar also). Finally, it can be concluded that the appearance of sheet-like structure might be possible inside the cores of magnetars (and rotating neutron stars also).

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