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High-density QCD phase transitions inside neutron stars: Glitches and gravitational waves

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Abstract. We discuss physics of exotic high baryon density QCD phases which are believed to exist in the core of a neutron star. This can provide a laboratory for exploring exotic physics such as axion emission, KK graviton production etc. Much of the physics of these high-density phases is model-dependent and not very well understood, especially the densities expected to occur inside neutron stars. We follow a different approach and use primarily universal aspects of the physics of different high-density phases and associated phase transitions. We study effects of density fluctuations during transitions with and without topological defect production and study the effect on pulsar timings due to changing moment of inertia of the star. We also discuss gravitational wave production due to rapidly changing quadrupole moment of the star due to these fluctuations.

Keywords. Pulsars; QCD phase transition; superfluidity; fluctuations; glitches; topological defects.

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1. Introduction

Neutron stars are born in supernova explosions with typical initial temperature of tens of MeV, and core density which can be a few times the nuclear saturation density. They cool rapidly during early stages, followed by a slow cooling phase. Neutrino emission is the most efficient source of energy loss during the cooling of the neutron star. Clearly, any other mode of cooling via (very) weakly coupled particles will affect the cooling strongly and hence will have strong observational constraints. The observed cooling curves of neutron stars strongly constrain such exotic models of new physics (e.g. from SN1987A). Effects of axion emission on the cooling of neutron star have been well studied for standard hadronic phase of the neutron star. However, it has not been much explored in very high-density regime with chiral symmetry restoration, or other high-density QCD phases which affect instanton processes, hence axion mass. Similarly, Kaluza–Klein (KK) gravitons in large extra dimension models can be strongly constrained by neutron star cooling. After production, these gravitons can be trapped in neutron star gravitational potential, and subsequent decaying of these gravitons to γ-rays can be detected. This has been used to constrain the number/size of extra dimensions.

It is clearly important for these studies that one understands the properties of neutron star matter. For example, cooling processes can be strongly affected by the presence of energy gap at the Fermi surface. This has been investigated in the context of superfluid phase of nucleons in the interior of the neutron star. All these studies can be dramatically affected when new phase structures of dense matter arise. Energy scale of the gap can change from a fraction of MeV (for neutron superfluid state) to about 100 MeV for the colour flavour locked (CFL) phase. Also, chiral symmetry breaking/restoration is highly non-trivial in very high-density phases of QCD. Thus, one needs detailed understanding of phase structure of these ultra-high density phases of neutron stars. This is important for interpretating any signals of new physics.

Further, there are other surprises in these phases of QCD. There was an early excitement about cosmic topological defects, like cosmic strings, monopoles, domain walls etc. Such objects were expected to arise in certain grand unification models. In particular, cosmic strings received much attention as possible candidates for providing density fluctuations needed for the structure formation. The interest in these objects faded with precision CMBR data which clearly showed that cosmic strings cannot explain the structure formation. Though, one should note that cosmic strings etc. are still very important as they can provide a direct signal of the physics of GUT scale, or even superstring physics. These cosmic defects are highly non-trivial field configurations with remarkable properties. They provide analogues of topological defects in standard condensed matter systems for relativistic quantum field theory.

It turns out that various high-density QCD phases produce similar topological defects, again in the context of relativistic quantum field theory. These could be appropriately called as astrophysical topological defects, instead of the cosmic topological defects like cosmic strings etc. In this paper, we shall discuss how these astrophysical defects can be detected from high precision observations of pulsar timings. These induce clear signatures, very specific to our models about correlation between modulations of pulsar signals with pulse timings. Most importantly, we shall show that the resulting density fluctuations can provide a new source of gravitational waves, with frequency in megahertz. LIGO is capable of upgrades for this frequency range. This can provide a powerful technique to study these phases and transitions inside compact stars.

2. QCD Phases

Exotic phases of QCD are believed to exist at high baryon density. At ultrahigh baryon density with very large chemical potential, asymptotic freedom makes perturbative calculations reliable. With one-gluon exchange quark–quark interaction being attractive in the 3* channel, possibility of BCS pairing of quarks arises, leading to colour superconductivity. One of these phases, the CFL phase, arises in the most symmetric case assuming three massless flavours (which is reasonable only for quark chemical potential much larger than strange quark mass). In this case, the quark–quark pairing is colour antisymmetric, spin antisymmetric, and flavour antisymmetric,

$$\left\langle q_i^\alpha q_j^\beta \right\rangle \sim \Delta_{\mathrm{CFL}} \left(\delta_i^\alpha \delta_j^\beta - \delta_j^\alpha \delta_i^\beta\right) = \Delta_{\mathrm{CFL}} \epsilon^{\alpha\beta n} \epsilon_{ijn}. \tag{1}$$

This pairing leads to the following spontaneous symmetry breaking pattern [1]:

$$G \equiv SU(3)_{\mathrm{colour}} \times SU(3)_{\mathrm{L}} \times SU(3)_{\mathrm{R}} \times U(1)_{\mathrm{B}} \rightarrow SU(3)_{\mathrm{colour+L+R}} \times Z_2 \equiv H. \tag{2}$$

Properties of these phases have been extensively explored [1]. In the CFL phase, colour $SU(3)$ is spontaneously broken. Further, chiral symmetry is spontaneously broken beyond density where chiral symmetry was restored (the standard QGP phase). Interestingly, rotated electromagnetism (mixture of photon and gluon) survives [1]. Spontaneous breaking of $SU(3)$ colour symmetry implies that all gluons become massive, hence the name colour superconductor. As the spontaneous breaking of chiral symmetry is not by a colour neutral quark–antiquark condensate, but by a coloured quark–quark condensate, there should be (coloured) hadron multiplets in this phase. Other possible quark pairings lead to different phases. For example, for 2 light flavours one gets the 2SC phase which breaks colour $SU(3)$ to colour $SU(2)$ symmetry. In this case, 5 out of 8 gluons become massive.

2.1 *Topological properties of the CFL phase*

The spontaneous symmetry breaking pattern for the CFL phase (eq. (2)) leads to a rich topology for the vacuum manifold. This leads to the existence of topological defetcs/objects as follows.

Homotopy groups of the vacuum manifold (G/H) and associated topological defects are as follows:

$\pi_0(\frac{G}{H}) = 1$, so no domain walls
$\pi_2(\frac{G}{H}) = 1$, so no monopoles
$\pi_1(\frac{G}{H}) = Z$ implies the existence of string defects, these are superfluid vortices.
$\pi_3(\frac{G}{H}) = Z \times Z$ implies two copies of skyrmions (baryons).

It is important to note that the conclusions about the existence of different topological defects as mentioned above were reached without any knowledge of details, such as the magnitude of gap parameter, transition temperature, nature or even the existence of phase transition. The considerations above are purely topological, hence are universal in nature. Such high-density QCD phases may arise inside the cores of neutron stars (or proto-black-holes). As we shall see, the form of signal (for pulsar timings, or the profile of gravitational waves) depends primarily on the geometry of defects. Thus, the qualitative aspects of these signals will have a universal character. Dynamical details will only control the magnitude of the signal, not its form.

3. Core of the neutron star and pulsar glitches

Pulsar observations provide extremely precise measurements of pulsar timings. We recall that the first detection of gravitational waves was done with these ultrahigh precision measurements of neuron star orbital parameter changes from gravitational wave emission. Pulsars show the phenomenon of glitches where there is a sudden increase in rotational frequency, followed by slow relaxation, over several months. Present understanding of glitches is in terms of crustquakes, or transfer of angular momentum due to depinning of clusters of superfluid vortices. Relatively recent observations show the phenomenon of antiglitches corresponding to the sudden slowing down of the rotation of the star. The model of depinning of vortices cannot account for these antiglitches.

4. Phase transitions and density fluctuations

Density fluctuations inevitably arise during phase transitions. In a first-order transition, random bubble nucleations lead to density fluctuations, with typical distance scales of interbubble separation. In a second-order transition, or smooth cross-over, density fluctuations with size scale of correlation domains arise. Further, scale-invariant density fluctuations result in the critical regime for continuous transitions. In any transition/cross-over, large-scale density fluctuations inevitably arise if topological defects are produced. If density fluctuations arise in the core of a pulsar, it will affect its moment of inertia (MI) and quadrupole moment Q. This can be detected by precision measurements of pulse shape/timing. These fluctuations also lead to rapid changes in the quadrupole moment of the star leading to emission of gravitational waves.

We first briefly consider hadron to QGP first-order transition due to the slow increase of central density of pulsar over millions of years. This can happen due to slow decrease in rotation rate or due to increase of mass due to accretion. We consider accretion case (so that we can use equations of non-rotating star, for simplicity). Typical accretion rate is about 10^{15}–10^{18} g/s. This means a few percent change in the mass of a solar mass neutron star in one million years. For strong supercooling, the density of the pulsar becomes supercritical by matter accretion in a macroscopically large core of radius R_0 before any bubble nucleation occurs. Subsequently, nucleated bubble sweeps the entire core with relativistic speed converting the supercritical core to QGP phase. Such a rapid phase transition will lead to sudden change in the MI of the star. We find that fractional changes in the MI as well as in the quardupole moment Q of the star can be 10^{-11}–10^{-6}, see ref. [2] for details. This will imply similar fractional changes in the rotation of the star and hence in the pulsar timings. As density fluctuations dissipate away, these changes in MI and Q will also disappear. Thus, we expect that due to phase transitions, net MI and Q of the neutron star will change. After density fluctuations dissipate away, MI will be restored to some level, and Q will be completely restored to its original value (as uniform phase change in spherical core does not change Q). This change in MI has the same pattern as for observed glitches, hence may provide an alternate explanation for these. Interestingly, depending on the sign of changes in MI, this can also easily account for antiglitches.

We shall see that these changes in MI and Q are completely generic. They happen for all types of density fluctuations produced in phase transitions. Implications of these density fluctuation-induced changes are as follows: Change in diagonal components of MI will result in rapid changes in rotation of the pulsar. As density fluctuations dissipate away, leading to a uniform new phase in the core, some part of the change in MI will be restored, but not fully. Note that this is exactly the pattern of glitches and antiglitches where often only a few percent of the change in rotation is recovered. Also, as we find changes of both $+$ and $-$ sign, glitches and antiglitches are both naturally accommodated in this picture (no such uniform explanation is present in the literature for both). Further, transient changes in the off-diagonal components of MI and Q will also be necessarily present. These are distinctive predictions of our model. Changes in off-diagonal components will lead to the wobbling of the star (in addition to any wobbling present initially). This will lead to modulation of pulse intensity as the direction of radiation emission wobbles. Thus, our model predicts that in association with rapid changes in pulsar timings, there should be modulation in pulse intensities. This is the distinctive prediction of our model. Vortex depinning model cannot lead to off-diagonal components of MI (all vortices point along the rotation axis).

An important prediction of our model arises from noting that rapid changes in quadrupole moment Q will lead to gravitational waves. Small values of Q/I, where I is the moment of inertia of the star, arising from density fluctuations (of order 10^{-10}) is more than compensated by the very short time-scale of microseconds. Fastest time scale for conventional mechanism of gravitational wave emission is milliseconds (from rotation), with Q/I of order 1/1000. Here, in our model, Q/I is about 10^{-10}, but the time-scale is at most microseconds. In fact, for topological defect-induced density fluctuations, the time-scale can be much shorter as defect network coarsens very fast. Thus, density fluctuations arising during phase transitions in compact astrophysical objects, like neutron stars, may provide a new source of gravitational radiation. The resulting values of strain and power are well within the reach of LIGO. However, LIGO is tuned for optimum frequency in kHz regime. It has possibilities of upgrades for MHz frequency (if motivated by physics considerations, no other known astrophysical sources require MHz frequency). It will be important to have these upgrades to detect such new sources of gravitational waves. This can open up new possibilities for very short-time dynamics happening inside the core of the neutron star. It is interesting to note that it is not possible to observe such signals of very small energy density fluctuations in heavy-ion collisions. It is the accuracy of pulsar observations which allows for precision measurement of very tiny density fluctuations.

We now consider density fluctuations arising due to the formation of topological defects. As we discussed above, different QCD phase transitions correspond to different symmetry breaking patterns. Associated defect geometries are therefore very different. For example, we saw that for CFL transition we get strings and textures. For hadron-QGP transition, using Polyakov loop order parameter, we get strings and domain walls (quite like axion models in the Universe) [3]. Density fluctuations arising due to the formation of topological defects in phase transition can be conveniently studied using the so-called Kibble mechanism. In this mechanism, defect formation generically happens during phase transition due to formation of uncorrelated domains. These topological defects may be extended objects (strings, domain walls, textures) and lead to large density fluctuations and the resulting defect network has universal character, and typically evolves in a scale-invariant manner, depending only on the underlying symmetries and space dimension. Thus, density fluctuations resulting from different topological defects have very specific characteristics. As changes in pulsar timings and intensity modulations sensitively depend on the nature of density fluctuations (and how they dissipate), such high precision observations can identify specific defect formation and hence specific symmetry breaking patterns. Thus, we can identify specific transitions occurring inside a pulsar. We have carried out simulations of defect formation (for small system sizes $\sim$ several 1000 fm) and tried to extrapolate to macroscopic sizes for the pattern of resulting density fluctuations. We find that the resulting values of fractional changes in MI and the quadrupole moment are of a magnitude which will give detectable signal for pulsar timings [2]. All these will give strong pulses of gravitational waves, though of very high frequency. These observations, along with pulse profile measurements (due to modulations from off-diagonal MI components) can pin down specific transition occurring inside the core of the neutron star. Some such phases may be reachable in heavy-ion collisions, in particular at FAIR and NICA, where they have to be detected by entirely different methods.

5. Conclusions and outlook

We conclude by emphasizing the main focus of our model that phase transitions occurring inside pulsar cores lead to density changes and density fluctuations, leaving imprints on pulsar timings. Random density fluctuations lead to non-zero off-diagonal components of MI which leads to the wobbling of the star, implying intensity modulation in association with pulsar timing changes. Correlation of these observations can pin down the specific transition occurring inside the neutron star core. We also argue that rapidly evolving fluctuations lead to rapid changes in quadrupole moment Q. Even with small magnitude of Q, this can provide a new source for gravitational waves due to very short time-scales. Time-scale for defect coarsening may be extremely small due to microscopic length scale involved in defect networks. On needs more realistic simulations. However, the physics of the model is simple, and so the effects is likely to survive for the realistic simulations also.

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