International Journal of Modern Physics E

Pulsars: Gigantic Nuclei

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What is the real nature of pulsars? This is essentially a question of the fundamental strong interaction between quarks at low-energy scale and hence of the non-perturbative quantum chromo-dynamics, the solution of which would certainly be meaningful for us to understand one of the seven millennium prize problems (i.e., "Yang-Mills Theory") named by the Clay Mathematical Institute. After a historical note, it is argued here that a pulsar is very similar to an extremely big nucleus, but is a little bit different from the *gigantic nucleus* speculated 80 years ago by L. Landau. The paper demonstrates the similarity between pulsars and gigantic nuclei from both points of view: the different manifestations of compact stars and the general behavior of the strong interaction.

1. What is a Gigantic Nucleus?

Let's begin with the *little* nucleus in normal matter. Atoms were supposed to be indivisible by ancient philosophers until J. J. Thomson who discovered a more fundamental unit in atom, the electron, by studying cathode rays in 1897, and explained the phenomena in the plum-pudding model in which the negatively charged electrons were distributed in a uniform medium of positive charge. In 1911, this scenario was challenged by the famous experiment of E. Rutherford, scattering of α-particles off gold atoms in foil, and a positive charge concentrated in a very small nucleus was speculated in the Rutherford model. However, it was a matter of big debate about the nuclear constitution of atoms although Rutherford postulated that "*Under some conditions, however, it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet*"[1], and that the doublet (latter called *neutron*) would be inside a nucleus.

What does a little nucleus behave like? It was G. Gamow who suggested to treat atomic nuclei as little droplets of incompressible nuclear fluid when he worked at the University of Copenhagen from 1928 to 1931.[2] This liquid drop model is still popular even an idea of solid nucleus was also addressed in 1974,[3] motivated by the fact that the giant resonance might resemble the vibration of an elastic solid.

It is a scientific miracle of the February 1932. Do remember three events in that month. (1) L. Landau at the age of 24 published a paper in which an idea of gigantic nucleus was presented:[4] "*We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.*" The paper had two notes: "Received 7 January 1932" at the beginning and ending with "February 1931, Zurich". (2) J. Chadwick published a paper with a title of "*Possible existence of a neutron*",[5] which was received on Feb. 17, 1932. (3) A letter of Chadwick was written on Feb. 24, 1932, and sent to Bohr, with the discussion of neutron and atom. We can then conclude that Landau speculated gigantic nucleus before the discovery of neutron.

The motivation for Landau's writing the paper was of duality. In the years around 1930, a hot topic was on the star equilibrium in gravity, particularly the maximum mass[6] of white dwarfs where electron degenerate pressure stands against gravity. What if a stellar mass is higher than the maximum one? Landau was thinking about two points: (1) huge gravitational energy should be released, and (2) the collapse could stop when atomic nuclei come in close contact. Landau's effort seeks to relate this scenario to energy source of stars, and his answer was that forming gigantic nuclei would be the origin of stellar energy. Certainly the answer was wrong, but it is the first time that mankind recognizes a kind of macroscopic matter (an extension of the microscopic droplet proposed by G. Gamow) at about nuclear saturation density, which is surely necessary for us to understand various extreme phenomena through astronomical observations.

It is worth noting that Landau did care about his idea of gigantic nucleus although he is famous for his fundamental contributions to condense matter physics, especially the theory of superfluidity. According to "*Complete list of L D Landau's works*" provided by Aksenteva,[7] Landau published totally six *Nature* papers but three were authored only by himself, listed as following.

(i) L. Landau, "Origin of stellar energy", *Nat.* 141, 333 (1938)
(ii) L. Landau, "The theory of phase transitions", *Nat.* 138, 840 (1936)
Brief message of "ZETF 7 (1937) 19, 627; Phys. Z. Sowj. 11 (1937) 26, 545"
(iii) L. Landau, "The intermediate state of supraconductors", *Nat.* 141, 688 (1938)
Brief message of "ZETF 13 (1943) 377; J. Phys. USSR 7 (1943) 99"

The first one was actually based upon that[4] published in 1932, and the latter two were summaries of previous works that might lead to his Nobel prize in physics in 1962. Why did Landau address again his idea about gigantic nucleus and stellar energy? It was said that Landau was submitting the manuscript to *Nature* in order to stand against his political pressure in 1937. The paper was published finally in 1938, but Landau was still jailed (he was in prison from 28 April 1938 to 29 April 1939). One can then see Landau's interests of stars from this real story.

Gigantic nuclei should certainly be neutron-rich if protons (p) and neutrons (n) are supposed to be elementary particles, because electrons (e) are *inside* a gigantic nucleus. One can easily come to the conclusion via considering the chemical equilibrium of the reaction of

$$e + p \longleftrightarrow n + \nu_e, \tag{1}$$

where the chemical potential of neutrino (ν_e) is negligible. It is then understandable that the item of gigantic nucleus was not popular but soon updated by "*neutron* *star*" in the scientific community after the discovery of neutron.

Is there any astronomical consequence of neutron star? Two astronomers, Baade & Zwicky,[8] conceived the idea that forming neutron stars could be the energy source of supernova rather than of stars, and they investigated the scenario from cosmic rays (ions) which "*are expelled from them* (supernovae) *at great speeds*" although the assumed mechanism to produce a neutron star ("*If neutrons are produced on the surface of an ordinary star they will 'rain' down towards the center if we assume that the light pressure on neutrons is practically zero*") was not rigorous. Hot neutron stars were suggested to exist in the cores of supernovae and to be detected as X-ray sources.[9] It was also conjectured that the stored energy in rotation of neutron stars would power supernova remnants.[10] Certainly the discovery of radio pulsars was a breakthrough,[11] and pulsars were soon identified as spinning neutron stars.[12]

Let's conclude this historical note by addressing the fact that L. Landau and G. Gamow were two in the group known as "Three Musketeers" at the University of Leningrad. Both of them were thinking about science-breaking questions there and benefited greatly from each other in their whole lives. Summarily, around 1930, Gamow proposed a liquid picture for microscopic nucleus, but Landau further suggested macroscopic nuclear matter inside gravity-bound objects. It is surprising that such stars had really been discovered! However, even after 80 years of research, we are still not very certain about the real nature of gigantic nuclei/neutron stars.

2. Two mistakes made by L. Landau at the age of 23

Constrained by the scientific culture in 1930s, Landau's conjecture about the gigantic nucleus had to include some concept incorrect. Let's discuss and analyze two mistakes made in Landau's paper published in 1932.[4]

Mistake 1: Quantum theory should be violated in gigantic nuclei so that a proton and an electron could be "*very close together*" (on a scale of femtometer, with a modern language). We know that an electron interacting with a proton via electromagnetic force can only make up a relatively *weak* system (scale order of Angstrom) of hydrogen if they obey quantum mechanism which has been well tested.

The reason that Landau made this mistake was the ignorance of *weak* interaction at that time. We now know that weak interaction could convert an electron and a proton to a new particle, neutron, via a reaction of Eq.(1).

In the standard model of particle physics, developed successfully in the last century, elemental fermions (quarks and leptons) and gauge bosons are the building blocks, rather than protons ($\{uud\}$) and neutrons ($\{udd\}$) that were supposed to be point-like particles in 1930s. Therefore the reaction of Eq.(1) is essentially converting a u-quark to a d-quark by $e + u \longleftrightarrow d + \nu_e$. In fact, besides u and d valence quarks inside a nucleon, there are totally six flavors of quarks, which can be divided into two groups according their masses: light flavors of quarks (u, d, s) with low masses and heavy ones (c, t, b) with masses $>$ GeV. The flavors can be changed by weak interaction although flavor conservation works during strong interaction. In this regime, an open question could then arise: Can a gigantic nucleus have strangeness since it would be easier to excite strange quarks than heavy quarks?

Mistake 2: Gravity could be the only interaction to determine the general property and the global structure of gigantic nuclei. Landau thought then that only gravitational energy release dominates and that gigantic nuclei should be gravity-bound, so that he wrote "*Thus we can regard a star as a body which has a neutronic core the steady growth of which liberates the energy which maintains the star at its high temperature; the condition at the boundary between the two phases is as usual the equality of chemical potential*" in 1937.

The reason that Landau made the second mistake was the ignorance of *strong* interaction at that time. The strong force could have at least two important consequences about gigantic nucleus. (1) Nuclear energy can be released via nuclear reactions, so that one can come to a correct conclusion: nuclear power is the origin of stellar energy. (2) It is possible that a gigantic nucleus would be self-bound by strong interaction, rather than gravity-bound, as in the case of a normal nucleus.

In a word, a lack of knowledge about two kinds of microscopic interactions (weak and strong) resulted in the mistakes made by Landau 1930s. 80 years later, it is necessary to modify and develop the science of gigantic nucleus, with the inclusion of strong and weak forces which play an important role in nuclear and particle physics, as well as in astrophysics. We are trying to do in the next section.

3. Gigantic Nuclei revised

Although the gigantic nucleus concept has been developed to be modern neutron star models, there do exit essential differences between little nuclei and gigantic ones. We think at least two major differences here. (1) Electrons are included in gigantic nuclei but not in little nuclei because of relatively large scale (the Compton wavelength is only $h/(m_e c) = 0.24\text{Å}$). (2) The average density of gigantic nuclei should be supra-nuclear density (a few nuclear saturation densities) due to gravitational force, while gravity would be negligible for little nuclei. These differences may result in a peculiarity of gigantic nucleus. Quick questions about a gigantic nucleus include: Are there still three quarks grouped together as in the case of baryon? Does it have strangeness? Is it still in a liquid state? After years of researches, we think that a gigantic nucleus is actually composed of quark clusters with strangeness and is in a solid state in order to understand different manifestations of pulsar-like compact stars.[13] Let's explain in §3 and §4, respectively.

The real state of matter in compact stars is certainly relevant to the QCD phase diagram in terms of temperature T vs. baryon chemical potential $\mu_{\rm B}$ (or baryon number density), which is truly a matter of debate in nuclear and particle physics. In the regime of low temperature, because of the asymptotic freedom nature, dense matter may change from a hadronic phase to a deconfined phase as baryon density increases. But a very serious problem is: can the density of realistic compact stars be high/low enough for quarks to become deconfined/confined?

We may approach the state of matter in compact stars along two directions.

An approach from hadronic state (a bottom-up scenario). Let's assume that quarks would not be deconfined in pulsars. However the confined state may not be simply that of hadrons because of those two differences as discussed above. We may expect that a light-flavor symmetry (i.e., that of strange matter, with approximately equal number densities of u, d and s quarks) would be restored when the baryon density and the length-scale of gigantic nucleus increase. We know that nucleon is the lightest baryon, but the typical energy of electrons would be order of 10^2 MeV (to be order of or even higher than the mass difference between s-quark and u/d-quark) if nucleus keeps not to be broken at supra-nuclear density, while electrons in strange matter is negligible. Additionally, gigantic nuclei of light-flavor symmetry might be ground state of cold matter at a few nuclear densities due to strong color interaction. Furthermore, the self-bound gigantic nuclei could be energetically favored because of huge gravitational energy release, as was noted by Landau 80 years ago.[4] Therefore, three flavors of quarks could be grouped together to form a new hadron-like confined state in gigantic nucleus, and this multi-quark state may move non-relativistically due to large mass and localized in lattice at low temperature. We may call this new state of strong-interaction as "*quark cluster*".

An approach from free quark state (a top-down scenario). Among the speculated states in the diagram, considerable theoretical efforts have been made to explore the Bardeen-Cooper-Schrieffer-like color-superconducting phases for cold matter at supra-nuclear density.[14] This is worth to do if the coupling between quarks in realistic compact stars is really relatively weak so that perturbative QCD (pQCD) works. It is known that pQCD would work reasonably well only for energy scale above 1 GeV at least, while the quark chemical potential is only ~ 0.4 GeV for typical pulsars (mass $\sim 1.4 M_\odot$ and radius ~ 10 km). It is then possible that the strong interaction between quarks in compact stars may result also in the formation of *quark clusters*, with a length scale l_q and an interaction energy E_q. An estimate from Heisenberg's relation gives if quarks are dressed, with mass $m_q \simeq 300$ MeV,

$$l_q \sim \frac{1}{\alpha_s}\frac{\hbar c}{m_q c^2} \simeq \frac{1}{\alpha_s}\ \mathrm{fm}, \quad E_q \sim \alpha_s^2 m_q c^2 \simeq 300\alpha_s^2\ \mathrm{MeV}. \tag{2}$$

This is dangerous for the Fermi state of matter since E_q is approaching and even greater than the potential ~ 0.4 GeV if the running coupling constant $\alpha_s > 1$, and a Dyson-Schwinger equation approach to non-perturbative QCD shows that the color coupling should be very strong rather weak, $\alpha_\mathrm{s} \gtrsim 2$ at a few nuclear densities in compact stars.[13] Quarks would thus be clustered and localized there.

Therefore a quark cluster phase is conjectured in the QCD phase diagram.[15] That phase should be in a liquid state at high temperature, but could be in a solid state when thermal kinematic energy is lower than the residual strong interaction energy between quark clusters. Pulsars are in the low temperature limit, and they would then be solid quark-cluster stars, a modified version of Landau's gigantic nuclei. A quark-cluster star would be very similar to a metal ball, but updating ions/nuclei and electromagnetic interaction in the latter by quark clusters and strong interaction in the former, respectively. It is worth noting that, because of small flavor symmetry broken, the number density of s-quarks is a little bit smaller than that of u/d-quarks. The total charge of quarks is then positive, which may result in the formation of crusts around quark-cluster stars.

What could be a realistic quark-cluster? We know that Λ particles (with structure *uds*) possess light-flavor symmetry, and one may think that a kind of quark clusters would be Λ-like. However, the interaction between Λ's is attractive, that would render more quarks grouped together. Motivated by recent lattice QCD simulations of the H-dibaryons (with structure *uuddss*), a possible kind of quark clusters, H-clusters, is proposed.[16] Besides a general understanding of different manifestations of compact stars, it is shown that the maximum mass of H-cluster stars (or simply H stars) could be well above $2M_\odot$ under reasonable parameters.

4. Observational supports for the revision?

What could be the essential differences between normal neutron stars (the old version of gigantic nucleus, but developed) and solid quark-cluster stars (the revised version of gigantic nucleus) by the observations of pulsar-like stars? We think there are two. (1) On the *surface*, particles are gravity-bound for neutron stars while matter is self-confined by strong force for quark-cluster stars. (2) The equation of state determines the *global* structure: liquid or rigid? soft or stiff?

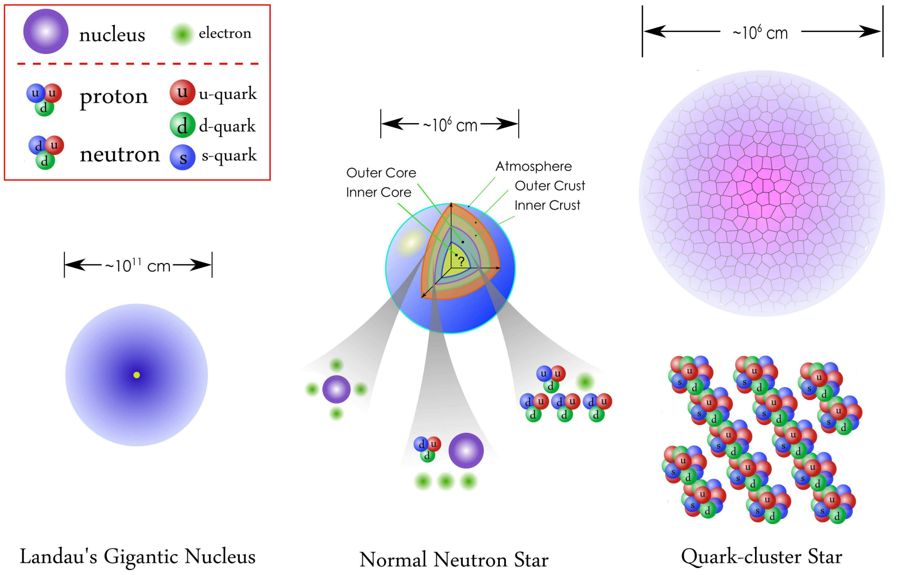
The *surface* difference has two implications: the mass-radius (M-R) relation of star and the binding energy of particle. Self-bound quark-cluster stars have non-zero surface density, and their radii usually increase as masses increase (specially, $M \propto R^3$ for low-mass quark-cluster stars with negligible gravity), while for a gravity-bound neutron star the radius decreases as the mass increases. The peculiar mass-radius relation of SAX J1808.4-3658 shows that the star could be a quark star.[17] Anyway, an intuitive awareness of the difference could be from the binding energy.

Pulsar-like stars are populated by radio pulsars, and it seems that all radio sub-pulses are drifting. These clear drifting sub-pulses suggest the existence of Ruderman-Sutherland-like gap-sparking and strong binding of particles on pulsar polar caps, but the calculated binding energy in neutron star models could not be so high. This problem could be naturally solved in bare quark-cluster star scenario due to the strong self-bound nature on surface.[18,19] In addition, the strong surface binding would result in extremely energetic exploding because the photon/lepton luminosity of a quark-cluster surface is not limited by the Eddington limit, and supernova and γ-ray bursts could then be photon/lepton-driven.[20,21,22] Besides, the observation of non-atomic thermal spectra of dead pulsars may also hint that there might not exist the atmospheres speculated in neutron star models, but that this observational feature could be a manifestation of quark-cluster stars.[23]

Let's turn to the *global* difference. As is addressed in the previous section, quark-cluster stars would be in a global solid state (like "cooked eggs"), while only crust is solid for normal neutron stars (like "raw eggs"). Spinning rigid body precesses naturally, either freely or by torque, and the observation of possible precessions of B1821-11[24] and others could suggest a global solid structure. It is said that quark stars cannot reproduce glitches detected soon after discovery of pulsars, but both normal glitch and slow glitch could be understood in solid quark cluster-star models.[25,26] A peculiar action of solid compact stars is star-quake, during which huge gravitational and elastic energy would be released. Quake-induced energy may power the flares and bursts of soft γ-ray repeaters and anomalous X-ray pulsars.[27]

Additionally, we note also here that the state equation of quark-cluster stars is stiff because of non-relativistic motion of quark clusters. It is well known that the state equation of extremely relativistic particles is soft, and hence it is a conventional idea that quark matter is soft. Nevertheless, theoretical calculations[28,29] show that there is plenty of parameter space for the maximum mass of quark-cluster stars to be higher than $2M_\odot$, as was measured in binary system of PSR J1614-2230.

H-nuggets? One consequence of quark-cluster phase could be the existence of quark nuggets composed of quark clusters. We may call those quark nuggets as H-nuggets if they are of H-clusters. Can we discover H-nuggets in cosmic rays?



Landau's Gigantic Nucleus

Normal Neutron Star

Quark-cluster Star

Fig. 1. Three neutron stars, old and new. (*Thanks to Junwei Yu for his artistic work of drawing.*)

5. Summary

80 years ago, an idea of gigantic nucleus was presented by Landau, who tried to understand the origin of stellar energy by combing the researches of gravity-bound star and Gamow's speculation of nuclear droplet. That idea develops then, especially after the discovery of pulsars, to be very elaborate models of normal neutron stars. It is also conjectured, from an astrophysical point of view,[30] that there would

exist a quark-cluster state in cold matter at a few nuclear densities, which could be necessary to understand different manifestations of pulsar-like compact stars. Pulsars could then be solid quark-cluster stars. This concept is shown in Fig. 1.

Let's conclude the paper by a famous sentence of P. W. Anderson (1923-): "*The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe*". As for the state of cold matter at realistic supra-nuclear density, we get embarrassed and much more difficult because the fundamental strong interaction law is still uncertain there and would be related to one of the seven Millennium Prize Problems.

Acknowledgements. I would like to thank Dr. Sergey Bastrukov for both historical and scientific discussions and acknowledge many contributions by members at the PKU pulsar group. This work is supported by the National Natural Science Foundation of China (grants 10935001 and 10973002), the National Basic Research Program of China (grant 2009CB824800), and the John Templeton Foundation.

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