Strange Quark Stars

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Abstract A nonmathematical review of strange (quark) stars is presented. After a historical notation of the research, we discuss the physics of strange stars, including the possible ways to identify them in astrophysics.

1 Historical Notes

Soon after the Fermi-Dirac form (in 1926) of statistical mechanics was proposed for particles which obey Pauli's exclusion principle (in 1925), Fowler (1926) realized that the electron degeneracy pressure can balance for those stars, called as white dwarfs, discovered by astronomers in 1914. Chandrasekhar's numerical calculation (1931) for a polytropic gas of extremely relativistic electrons found a unique mass, which was interpreted as a mass limit of white dwarfs. Landau (1932) presented an elementary explanation of the Chandrasekhar limit by considering the lowest total energy of stars, and recognized that increasing density favors energetically the formation of neutrons, discovered only several months before by Chadwick, through the action $p + e^- \leftrightarrow n + \nu_e$. A very massive compact object with much high density may have almost neutrons in the chemical equilibrium, which was then called as *neutron stars* (NSs).

Detailed calculations of NS structures showed (e.g., Oppenheimer & Volkoff 1939) that an NS can have a mass of $\sim 1M_\odot$, but is only $\sim 10\,$km in radius, which makes it hard to be observed by astronomers. However, on one hand, a few authors indeed investigated possible astrophysical implications of NSs. For example, Baade & Zwicky (1934) combined the researches of supernovae, cosmic rays, and NSs, and suggested that NSs may form after supernovae; Pacini (1967) even proposed that the stored energy in rotational form of an NS could be pumped into the supernova remnant by emitting electromagnetic waves. On the other hand, NS models were developed with improved treatments of equation of states, involving not only $\{n, p, e^-\}$, but also mesons and hyperons. The cooling behavior of NSs was also initiated in 1960s due to the discovery of X-ray sources which were at first thought mistakenly to be the thermal emission from NSs.

The discovery of *radio pulsars* by Hewish & Bell (and their coauthors 1968) is a breakthrough in the study, and this kind of stars were soon identified as spinning NSs by Gold (1968). Since then more and more discoveries in other wave bands have broadened greatly our knowledge about these pulsar-like compact stars, including X-ray pulsars, X-ray bursts, anomalous X-ray pulsars, soft γ-ray repeaters, and ROSAT-discovered "isolated neutron stars". It is still a current concept among astrophysicists that such stars are really NSs. NS studies are going on in two major directions: 1, the emission mechanisms for the stars, both rotation-powered and accretion-powered; 2, the NS interior physics.

However, neutrons and protons are in fact *not* structureless points although they were thought to be elementary particles in 1930s; they (and other hadrons) are composed of *quarks* proposed by Gell-Mann and Zweig, respectively, in 1964. The quark model for hadrons developed effectively in 1960s, and Ivanenko & Kurdgelaidze (1969) began to suggest a quark core in massive compact stars. Itoh (1970) speculated about the exist of 3-flavor *full* quark stars (since only u, d and s quarks were recognized at that time), and even calculated the hydrostatic equilibrium of such quark stars which are now called as *strange stars* (SSs). Is it possible that strange stars really exist in nature? The possibility increases greatly if the Bodmer-Witten's conjecture, i.e., strange quark matter (next section) is absolutely stable, is correct (Bodmer 1971, Witten 1984). Farhi & Jaffe's (1984) calculation in the MIT bag model showed that the energy per baryon of strange matter is lower than that of nucleus for QCD parameters within rather wide range although we can hardly prove whether the Bodmer-Witten's conjecture is correct or not from first principles. Haensel, Zdunik & Schaeffer (1986) and Alcock, Farhi & Olinto (1986) then modelled SSs, and found that SSs can also have typical mass (of $\sim 1-2M_\odot$) and radius (of ~ 10 km), which means that *the pulsar-like stars believed previously to be NSs might actually be SSs.*

2 Strange Matter and Strange Stars

One of the most greatest achievements in the last century is the construction of the standard model in particle physics, which asserts that the material in the universe is made up of elementary fermions (divided into quarks and leptons) interacting though gauge bosons: photon (electromagnetic), $W^\pm$ and Z^0 (weak), 8 types of gluons (strong), and graviton (gravitational). There are totally 62 types of "building blocks" in the model. Besides the 13 types of gauge bosons, there are three generations of fermions (1st: $\{\nu_e$, e; u, d$\}$, 2nd: $\{\nu_\mu$, μ; c, s$\}$, and 3rd: $\{\nu_\tau$, τ; t, b$\}$. Note that each types of quarks has three colors) and their antiparticles. The final one, which is still not discovered, is the Higgs particle that is responsible for the origin of mass.

As is well known that the nucleus of an atom is composed of nucleons (protons and neutrons), whilst nucleons are of quarks (proton = {uud}, neutron = {udd}). It is expected that the confined quarks may become free as long as the energy density (temperature or baryon number density) is high enough, and a quark-gluon-plasma (QGP) state then forms. This new state has not been found with certainty yet. Unfortunately, the critical values, at which a phase transition from hadron gas state to QGP occurs, can not yet obtained exactly in the standard model of particle physics.

Strange (*quark*) *matter* could be such a kind of QGP, which may composed of equal numbers of u, d, and s quarks, and possible a small ratio of electrons, which may have baryons from several hundreds called as *strangelets*, to about that of our sun, called as *strange stars* (SS). SSs are not really "*strange*"; they, with strangeness, are just named after the *strange* quark.

Although the SS idea is not new, SS identification becomes a hot topic only in recent years due to advanced techniques in space science. Since SSs may have similar masses and radii to those of NSs, which are conventional quantities observable in astronomy, it is very difficult to find observational signals of quark matter in the pulsar-like stars. It was argued that the SS and NS cooling behaviors could be distinguishable, since SSs may cool much faster than NSs (e.g. Pizzochero 1991). However, recent more complete analyses on this issue indicate that this may be impossible except for the first ~30 years after their births (Schaab et al. 1997). Nevertheless, the author thinks there may still be three effective ways to do.

1. The minimum rotation periods of SSs are smaller than that of NSs. Rotating stars composed of ideal fluid are subject to rotation-mode instability, which leads to the loss of rotation energy by gravitational radiation and results in substantial spindown. However the matter of a real star is not ideal but has viscosity; the calculated bulk viscosity, based

on the work of Wang & Lu (1984), of strange matter is much higher than that of neutron matter although their shear viscosities are similar; therefore SSs could have smaller periods at which their higher viscosity can prevent them from developing the instability (Madsen 1998). The 2.14 ms optical source in SN 1987A (Middleditch et al 2000) should be an SS if being confirmed in further observations.

2. The approximate mass-radius ($M - R$) relations of SSs ($M \propto R^3$) are in surprising contrast to that of NSs ($M \propto R^{-3}$), and SSs can have much small radii. Comparisons of observation-determined relations in X-ray binaries with modelled ones may thus tell if an object is an NS or an SS (Li et al. 1999). Also, a pulsar-like star with radius $\lesssim 8$ km could be an SS (Drake et al. 2002).

3. There are striking differences between the surfaces of bare strange stars (BSSs) and that of NSs. The very properties of the quark surface, e.g., strong bounding of particles, abrupt density change from $\sim 4 \times 10^{14}$ g/cm^3 to ~ 0 in ~ 1 fm, and strong electric fields, may eventually help us to identify a BSS. There may be three parts of possible evidence for BSSs. a. The RS-type (Ruderman & Sutherland 1975) sparking model, with an "user friendly" nature, faces at least two difficulties for NSs: the binding energy problem and the antipulsar issue, which can be solved completely if radio pulsars are BSSs (Xu et al. 1999). b. The strong binding of quark surface may help to constrain the fireball of SGR 0526-66 (Zhang et al. 2000, Usov 2001). c. BSSs are expected to have featureless spectra (of both surface thermal and magnetospheric non-thermal components) since no ion is above the quark surface nor in the magnetosphere, except for electron cyclotron lines due to the Landau levels appearing in strong fields (Xu & Qiao 1998, Xu 2002). Recent observations known hitherto of several pulsar-like stars actually show featureless spectra except for two sources 1E1207 and SGR1806, the lines of which may originate from Landau level transitions in suitable field strength for the space facilities (Xu et al. 2003).

3 Conclusions

The theoretical bases of SSs are, to some extent, solid in physics and the formation of strange quark stars is possible in astrophysics; SSs could thus exist. Although each of the observed phenomena from pulsar-like compact stars may be interpreted under the NS regime with unusual or artificial physical properties, it could be a simple and natural way to understand the observations by updating NSs with SSs. The Nobel physics prizes had awarded pulsar researchers two times for discovering the first radio pulsar and checking the general theory of relativity with strong gravity, respectively. Pulsar researchers could be awarded for the third time if strange stars are identified.

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