

Low-mass bare strange stars

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Abstract

Strange stars with low masses are suggested to exist in reality, the origin of which could be via accretion-induced collapse of white dwarfs. Such a strange star is likely bare, and would thus spin very fast, even to a period of <0.1 ms. Strange stars with low masses may differ from those with solar masses in various astrophysical appearances. Observations to test this “low-mass” idea are proposed. © 2005 COSPAR. Published by Elsevier Ltd. All rights reserved.

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1. Introduction

The existence of quark matter is a direct consequence of the asymptotically free nature of the strong interaction, which was proved in 1973 based on non-Abelian gauge theories. How can we find quark matter in reality? Besides the exploration in relativistic heavy ion colliders, strange (quark) stars, which are composed of almost equal numbers of u , d , and s quarks, are likely the stable bulk quark matter expected to be born after supernova explosions. The knowledge of elementary color interaction could be improved greatly via studying pulsars if they are strange stars, rather than normal neutron stars.

Pulsar-like stars could have very low masses in strange star models, because the mass of strange quark matter can be as low as a few hundreds of baryons due to color confinement, though the maximum mass can be order of M_{\odot} . Low-mass bare strange stars and relevant issues are studied in Xu (2005), including the period evolution in both rotation- and accretion-powered phases, the proposal that pulsar strong magnetic fields are ferromagnetism originated, the suggestion that the quark surfaces could be essential for successful supernova explosions of both solar- and low-mass strange stars, some candidates with low masses, and

possible observational tests. The low-mass strange stars are to be studied further in this paper, with attention being paid to their astrophysical appearances to identify one.

2. Possible origin of low-mass strange stars

Fermion stars stand against gravity by degenerate pressures, but are failed to do so if their masses, M , are higher than the mass limits, M_{ch} . Electron-degenerated matter (e.g., white dwarfs) should collapse,¹ and the gravitational (and maybe others) energy release may result in mass-ejection, when $M > M_{\text{ch}}$. After collapse, neutron-rich hadron matter may emerge temporarily, and then the degenerate pressure of a deeper layer of constituents below neutrons, the quarks, could counter-balance gravity if the density is high enough to de-confine quarks. A quark star is thus formed, and the star could be bare and with strangeness if the Witten’s conjecture, that bulk strange quark matter is absolutely stable, is correct.

Two scenarios for the collapse of electron-degenerated matter. (1) The iron-cores in the center of evolved massive stars are degenerate, the masses of which increase as nuclear fusion processes, and the cores therefore have to collapse if $M > M_{\text{ch}}$. (2) The mass of an accreting (from its binary or

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¹ Another possibility is an unstable thermal nuclear burst when $M \sim M_{\text{ch}}$, which appears as a Type Ia supernova explosion.

just of fall-back interstellar-medium) white dwarf increases, and will collapse finally. The former is one of the conventional mechanisms of supernova explosions, and the later is the so-called accretion-induced collapse (AIC) of white dwarfs (of CO or O-Ne-Mg). Whether an AIC process can result in the formation of a neutron stars (or a quark star) is still a matter of debate both observationally and theoretically. Nevertheless, if both scenarios can produce quark stars, the properties of residual quark stars may not be the same, since one scenario differs significantly from the other. Xu (2005) suggests that quark stars with low masses may form in AIC processes, while iron-core collapses could generally create normal-mass quark stars.

Actually, there are some hints of AIC-produced neutron stars. A general review on the possible connection between white dwarfs and neutron stars can be find in Canal and Gutiérrez (1997), and a short review on applying the AIC-idea to explain various observations in Fryer et al. (1999). The existence of pulsar-like stars with low-mass ($\sim M_\odot$) companion raises a question: how might such systems have survived to core-collapse supernovae without being disrupted by strong mass-ejection (e.g. a $20M_\odot$ -progenitor will eject $\sim 18M_\odot$ material after explosion)? It is suggestive that millisecond pulsars are born via AIC of white dwarfs to avoid those troublesome issues, but assuming currently that the mass-ejection is small during AIC. This assumption may not be reasonable in view of the fact that most of the progenitor mass would be ejected during an iron-core collapse. If mass-ejections are similar in these two cases, one have to conclude that AIC-originated pulsars could be low massive.

Low-mass millisecond pulsar idea could not be so good in the normal neutron star model, but sounds reasonable in the strange star model. Low-mass neutron stars have large radii, which could not rotate very fast. *Note:* the Kepler period of the minimal mass neutron star could be (mass $\sim 0.1M_\odot$ and radius ~ 160 km) $P_k = 2\pi/\sqrt{GM/R^3} \simeq 110$ ms, which is much larger than the period of millisecond pulsars (1–50 ms). However, low-mass bare strange stars have an advantage of fast rotation (Xu, 2005). In this sense, simulating the AIC process (e.g., to know the mass-ejection) could be helpful for identifying quark stars. In addition, a rapid rotating star in the AGB-phase may probably have enough mass to collapse when the star spins down. We may expect that a great percentage of millisecond pulsars (through a channel of (2–8) M_\odot -star \rightarrow white dwarf \rightarrow AIC \rightarrow low-mass strange star) exist in the Galaxy due to the high population of stars with low and intermediate masses.

It is not clear whether the very little timing noise observed in millisecond pulsars relates to the low masses of such pulsars. Intuitively, an active (quiet) quantity varies more (less) significantly. However the spin frequency, Ω , of pulsars does not obey this rule: the timing noise is high for low Ω (normal pulsars), but is low for high Ω (millisecond pulsars). Although a few models are invented to understand this unusual issue, a simple suggestion could be that

those two kinds of pulsars have different masses, since an object (e.g., a millisecond pulsar) with low mass could be less active and thus stable.

3. The conditions for keeping strange stars bare

It is worth knowing whether *bare* strange stars are ubiquitous, since the exposed quark surfaces are very important for us to identify strange stars and to receive information directly from quark matter. A newborn strange star should be bare due to detonating combustion, but it could be crusted in its later history with high accretion rate (Xu, 2002).

In case of low-mass bare strange stars, two conditions should be satisfied in order for keeping them bare. (1) A single accreted ion (e.g., a proton) should have enough kinematic energy to penetrate the Coulomb barrier: $GMm_p/R > \sim V_q$. The Coulomb barrier, V_q , is model dependent, which varies from ~ 20 MeV to even ~ 0.2 MeV (in cases of low strange quark mass and high color coupling). Approximating $M = (4/3)\pi R^3(4B)$ (B is the bag constant), one has

$$M > \sim \sqrt{\frac{3V_q^3}{16\pi B G^3 m_p^3}} \simeq 6.5 \times 10^{-4} V_{q1}^{3/2} B_{60}^{1/2} M_\odot \quad (1)$$

from the first condition, where $V_q = V_{q1}$ MeV, $B = B_{60} \times 60$ MeV fm $^{-3}$. (2) The accreting material is not halted significantly even near stellar surfaces. The critical accretion luminosity, beyond which crusts form, is (Xu, 2002),

$$L^* = \frac{32\sqrt{2}\pi^{5/2}\sqrt{c}Gm_p B}{3\varepsilon\sigma_\tau} \frac{R^{7/2}}{P^{1/2}} \simeq 8 \times 10^{33} \frac{R_1^{7/2}}{\varepsilon P_{ms}^{1/2}} \text{erg/s}, \quad (2)$$

where radius $R = R_1$ km, spin period $P = P_{ms}$ ms, and the effect, that only $\varepsilon < 1$ times of the accretion energy has been re-emitted above polar cap, has been included. It is not surprising that some of the nearby sources discovered recently (e.g., CCOs, DTNs, etc.) are actually low-mass *bare* strange stars since the luminosity of these objects is generally much smaller than $\sim 10^{35}$ erg/s.

Crusts forms if one of the two conditions cannot be satisfied. The accretion rate of a star moving in a medium with density $\rho = \rho_{24} \times 10^{-24}$ g/cm 3 is $\sim 10^{-18} M_1^2 V_7^{-3} \rho_{24} M_\odot \text{yr}^{-1}$, where the stellar mass $M = M_1 M_\odot$, the velocity $V = V_7 \times 10^7$ cm/s. Even for an accretion of Hubble time ($\sim 10^{10}$ years), the crust mass could be order of $\sim 10^{-8} M_1^2 V_7^{-3} \rho_{24} M_\odot$, which is very likely to be much smaller than the maximum crust mass, $10^{-6\sim-5} M_\odot$. The crusts might then be very thin, and the radii of low-mass strange stars should therefore be very small even for crusted ones. This is very helpful to identify strange stars.

4. Evolutional tracks of pulsar-like stars?

Besides radio-loud pulsars, radio-quiet pulsar-like compact objects are also discovered recently in X-ray bands, which include soft gamma-ray repeaters (SGRs) and anom-

alous X-ray pulsars (AXPs) (both have X-ray luminosity $L_x \sim 10^{34-35}$ erg/s), compact center objects (CCOs, $L_x \sim 10^{33-34}$ erg/s), and dim thermal Neutron stars (DTNs, $L_x \sim 10^{32-33}$ erg/s). Why do pulsar-like stars behave so diversely?

Many factors may affect the star's appearances, whereas we note that two parameters could be very important for their evolution scenarios: *environmental density* and *stellar mass*. A dense environment may be responsible for leaving a remnant-nebula after a supernova and for resulting possibly in a fallback accretion (e.g., via disk) around the compact star. Various astrophysical manifestations could then be due to differences of both the stellar masses and the accretion stages. The supernova remnants with non-pulsars have all been identified with SN IIL/b, which shows that the center compact objects have the strongest interaction with the surrounding medium (Chevalier, 2005). Therefore, AXPs/SGRs with remnants and CCOs could be born in dense environments, but DTNs in less dense ISM. The compact stars of SGRs/AXPs might be of solar masses, and their bursts could be of starquake-induced magnetic-energy release or of bombardments by strange-planets (Xu, 2004). In contrast, CCOs and DTNs without bursts have low masses. DTNs should be very fast rotators provided that they are born in a sparse ISM. We may expect that a DTN (e.g., RX J1856) may evolve to a state, where only Planck-like X-ray is radiated, without any extra UV-optical emission component, when its circum-stellar material dissipates by the so-called “propeller” mechanism.

5. Observational tests for the “low-mass” idea

Several ways, to be summarized, are proposed to test the “low-mass” idea.

1. *Dust emission around pulsar-like stars.* Accretion models are suggested to explain millisecond pulsars (“recycled”), CCOs, DTNs, and AXP/SGRs, but the accretion modes around these pulsar-like stars are still not yet clear. Anyway, in case of disk accretion, the central temperature, as a function of distance to the star, r , in the standard model (the α -disk) is $T_c = 1.2\alpha^{-1/5}\dot{M}_{16}^{3/10}M_1^{1/4}r_{10}^{-3/4}$ eV for $r \gg R$ (Frank et al., 1992), where $r_{10} = r/(10^{10}$ cm), $\dot{M}_{16} = \dot{M}/(10^{16}$ g/s), and the α -prescription of viscosity is taken. We see then that, outside the light-cylinder, the disk around a low-mass strange star would have $T_c \sim 0.1$ eV, which emits in sub-millimeter bands. In addition, normal planets that are still embedded in young circumstellar disks could also contribute much submillimeter emission (Wolf and D’Angelo, 2004). It is thus important to test models (Xu, 2005) for pulsar-like stars by detecting dust emission (with *Spitzer* and *SCUBA*, etc.).
2. *Determination the radii of distant pulsar-like stars.* A few ultra-compact binaries were discovered (i.e., the orbital periods, P_{orb} , is very short), which include 4U 1543-

624 ($P_{\text{orb}} = 18.2$ min), 4U 1820-30 ($P_{\text{orb}} = 11$ min), RX J1914.4 + 2456 ($P_{\text{orb}} = 569$ s), RX J0806.3 + 1527 ($P_{\text{orb}} = 321$ s). Such ultrashort period binaries are supposed to be double degenerated, possibly to be “NS + WD” systems. For instance, the low-mass X-ray binary, 4U 1543-624, has likely a companion of a C-O white dwarf with mass $\sim 0.03M_{\odot}$ (Wang and Chakrabarty, 2004). However, an alternative possibility for the nature of these binaries might be that they could be “WD + low-mass strange star” systems. This idea could be tested by future X-ray interference telescopes (e.g., *MAXIM*) with an angular resolution of $0.1\mu\text{arcsec}$, because a low-mass WD with radius $\sim 10^4$ km could be imaged (having angular size of $\sim 0.7\mu\text{arcsec}$ at a distance of 100 pc), but a low-mass strange star (or a strange planet) is still a point-source even observed by such an advanced telescope.

3. *Gravitational wave detection.* Detection of gravitational waves can certainly test the general theory of relativity, and also open a new window for us to observe astrophysical phenomena. Normal neutron stars could be a kind of gravitational-wave sources, both in the birth stages (Andersson et al., 2002) and in their later evolutions when glitches occur (Andersson and Comer, 2001). However, if pulsar-like stars are actually low-mass strange stars, and could be solidified soon after the birth stage when neutrino cooling dominates (if the melting temperature is order of > 1 MeV), we should not be able detect the waves, especially during glitches (Andersson and Comer, 2001). We propose thus to check these issues by *LISA* and *LIGO*.
4. *Searching for sub-millisecond pulsars.* Normal neutron stars can not spin with frequencies less than $\sim 0.5M_1^{1/2}R_6^{-3/2}$ ms ($R_6 = R/10^6$ cm), but low-mass bare strange stars can, even less than 0.1 ms (Xu, 2005). A possibility arises then to answer the question, what the nature of pulsar-like stars is, through searching for sub-millisecond pulsars in radio as well as in X-ray (and maybe other) bands. The shortest period of pulsars (PSR 1937 + 21) is 1.558 ms, and the investigation could also probably lead to breaking this record. We need thus a much short sampling time, and would deal with then a huge amount of data in order to find a sub-millisecond pulsars.

6. Conclusions

We have studied further low-mass bare strange stars, in addition to the work of Xu (2005). Low-masses strange stars could form via AIC of CO or O-Ne-Mg white dwarfs if most of the white dwarf masses are ejected during explosion, being similar to the case of core-collapse supernova of evolved massive stars. Ions accreted onto a bare strange star surface may have enough kinematic energy to penetrate the Coulomb barrier as long as the stellar mass is higher than $\sim 10^{-4}M_{\odot}$ and the luminosity is not much higher than $\sim 10^{34}$ erg/s. Such a strange star would thus keep to be bare even in an accretion phase. A low-mass

bare strange star can spin very fast, even to a period of <0.1 ms, due to the color-confinement by itself. Various astrophysical manifestations of pulsar-like stars may depend on their circumstellar density, but also on the stellar masses of residual stars. Observations to test this “low-mass” idea are presented, including detecting dust emission and gravitational wave, geometrically determining stellar radii, and searching for sub-millisecond pulsars.

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