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Archives of Physics Research, 2010, 1 (3):89-110
(http://scholarsresearchlibrary.com/archive.html)

ISSN 0976-0970
CODEN (USA): APRRC7

Astrophysical relevance of Strange Quarks

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ABSTRACT

In this contribution, peculiarities in the nature of strange quarks in relevance to astrophysics are investigated. The absolute stability of strange quark matter is a viable possibility and immensely affects physics at the astrophysical scale. Relativistic heavy-ion reactions offer a stage to produce this exotic state of matter and we have discussed the enhanced production of strange particles during these reactions within the framework of quark-gluon plasma (QGP) along with its observable implications. The role of strangeness for compact star phenomenology is explored. Emphasis is laid upon the possibility of existence of a third family of strange quark stars and its study help in revealing a number of unexplored features of the cosmos. Bag model parameters have been used to determine some integral parameters for a sequence of strange stars with crust and strange dwarfs constructed out of strange quark matter crust. A comparative analysis is performed between the strange and neutron stars and the strange and white dwarfs based upon these intrinsic parameters and paramount differences are observed.

PACS numbers: 12.38.Mh, 25.75.Nq, 14.65.-q, 97.60.Jd, 26.60.-c
Keywords: strangeness, strange stars, quark-gluon plasma, deconfinement.

INTRODUCTION

The last few years witnessed the inclusion of strangeness as another degree of freedom in astrophysical systems. The intriguing strange quarks have far reaching implications on certain unexplored features of the cosmos and could unravel some mysteries of the Universe. Strangeness walks hand in hand as an interrogatory feature right from the birth of the Universe that is from big bang to the end of stellar evolution. The astrophysical domain of strange quarks spans over the existence of a stable hypothetical state of matter called strange quark matter to the possible existence of strange stars and it also serves as an evident signature for the presence of QGP. In this paper, we will outline some recent developments in the study of matter with strangeness under extreme conditions with relevance to astrophysics and will discuss features that are leading to the rapid growth of this field, both on theoretical as well as experimental fronts.

The intimacy between astrophysics and strange quarks depends strongly upon the strange quark matter hypothesis. It states that for a collection of more than a few hundred u, d and s quarks, the energy per baryon E/A of strange quark matter (SQM) can be well below the energy per baryon of the most stable atomic nuclei (such as iron or nickel). Thus, everything which we see around us is in the metastable state and if conditions for the creation of net strangeness are met, the matter would not make back to ordinary hadrons. The physics of SQM can have an intimate relationship with the QGP state and we could study deconfinement at low temperatures. The ultra-relativistic heavy-ion collisions aim at creating mini Big-Bang in the laboratory and an enhanced production of strange particles during these collisions provide evident signatures for the presence of QGP and help in developing a connection between Astrophysics and Heavy-Ion Physics. Thus, the heavy ion reactions exhibit replicas of the situation created during the birth of the universe and enable physicists to study the behaviour and properties of big-bang matter in laboratory and help in studying how the elementary properties of matter change in deconfined vacuum state.

There is a possibility of existence of hyperstars, compact stars composed of strongly attractive hyperonic matter connected to strange hadronic matter and MEMOs (hypernuclei containing strange baryons). The presence of hyperstars relies solely upon the assumption of existence of SQM. Physicists [1,2] are looking forward for a possible existence of these new class of compact stars completely made up of SQM, which are called strange stars. There are indications that some earlier detected neutron stars could be strange stars or in fact could carry strangeness in the interior [3].

In this paper we have determined some integral parameters of strange stars with crust and strange dwarfs by employing the bag model parameters of the equation of state of SQM to two different models. Series of tabulated data has been used to perform a comparison between the strange and the neutron stars and also between strange and white dwarfs. Discriminatory features amongst the above are projected out by plotting these integral parameters against each other and this helped us in distinguishing the strange astrophysical objects from their non- strange counterparts.

In section 2, we have discussed the enhanced production of strange particles in heavy-ion reactions followed by section 3, where strangeness distillation is witnessed as a possible phenomenon for the production of strangelets. SQM and the consequences of its stability are discussed in section 4 and 5 respectively. Strange stars and their intrinsic features are studied in section 6. In section 7, we have modelled the strange star phenomenology using the bag model parameters. Section 8 deals with a brief introduction to Multiquark states, followed by conclusion in the last section.

2. Strange particles enhancement in heavy ion reactions:-Signature for the presence of QGP

The only unambiguous way to detect the transient existence of a QGP in heavy ion reactions, is through the observation of experimentally produced exotic remnants, most evidently, the enhanced production of strange particles in heavy ion collision reactions [4]. The equation of state of hot and dense hadronic matter created in these collisions is characterized by means of a phase diagram between baryon density and temperature. Now, at some critical temperature, the non-strange baryon density eventually witnesses a phase transition to a deconfined QGP state. The net strangeness is incorporated as a new degree of freedom for the equation of state to be passed through the heavy ion collisions.

Strange particles are relatively easy to detect by the tracks left behind by their decay products because the strange particles are naturally radioactive and their decay mode is through weak interactions. The time scale of this mode is extremely long as compared to the nuclear collision time. With greatly differing reaction rates in the medium, hadrons with varying strangeness content decouple at different times from the evolving system. Today, the evidence for QGP at various accelerator centres is quite overwhelming, yet very debatable. However, there is unanimity among physicists about significantly enhanced production of strange particles as a consequence of formation of QGP.

For enhanced strangeness production, the kinematic threshold energy in the case of QGP is relatively lower than in the case of hadron gas. In a QGP, strangeness production occurs through the following reaction.

$$q\bar{q} \rightarrow s\bar{s} \quad ; \quad g\bar{g} \rightarrow s\bar{s}$$

The required threshold energy is $2m_s$~300 MeV (bare mass of strange quark=150 MeV). The gluon fusion channel is a dominant one in which the gluons fuse together to produce quark-anti quark pairs in the plasma and thus the subsequent hadronzation process lead to the formation of relatively large number of composite particles containing one or more strange quarks [5]. The gluon fusion channel is not accessible in normal collisions among hadrons. The formation time of QGP lies between t=0.2-0.8 fm/c. It is the time required for the gluon gas to reach initial chemical equilibrium. Assuming chemical gluon equilibrium, strangeness production by gluon fusion sets in at that time. Thus after a very short equilibration time, the strangeness saturates the phase space in a baryon-rich environment. The equilibration time may actually be shorter than the duration of nuclear collision. In fact, given the short hadronic interaction scale, the lifespan of strangeness can be considered infinite.

The strange quarks and anti quarks observed in heavy ion reactions are freshly cooked from the kinetic energy of the colliding nuclei unlike the up and the down quarks which are brought into reaction by the colliding nuclei. This feature is supported by the fact that the drag forces of flowing matter is to a large extent different for strange baryon and antibaryon pair. Also, it is evident that at the time of particle freeze out, there is a considerable transverse/ radial collective flow. Thereby, we can say that the strange baryons and antibaryons are not dragged along the confined matter. Rather they must have been formed in coalescence of flowing matter. Actually, it is a strange fact that the mass of the strange quark and antiquark is equivalent to the temperature or energy at which the nucleons (protons and neutrons) and other hadrons dissolve into quarks. The quark gluon plasma is produced at a temperature ≥200-300 MeV, with a surviving time scale ≥0.5fm/c and energy densities of about 3-4 GeV/fm^3[5]. At this stage, charmonia formation is suppressed and strangeness is enhanced. The chemical temperature of SPS and RHIC [6,7] is T_{Chem}=165-170 MeV (energy density of 1GeV/fm^3) and we are aware that the mass of the strange quark is about m_s=150 MeV. This mass shows small variation with respect to temperature. For example, a higher temperature would lead to an increase in mass. The mass of strange quark at temperature T=182 MeV is m_s(T=182MeV)= 200MeV. Thus, it is clear that abundance of strange quark is sensitive to the condition, structure and dynamics of the deconfined matter phase.

It is worth noting that strange particle enhancement in heavy ion reactions is magnified from nucleon-nucleon to nucleus-nucleus collisions with strong enhancements for doubly and triply strange baryons. Some enhancements can occur even in the absence of quark gluon plasma. To solve this critical situation, the enhancements for particles carrying two and three quarks were measured separately. In proton-proton (p+p) collisions at RHIC energy, it was observed that enhancements occur upto 10 times more for Ξ (2s+1d) and Ω(3s). The experimental observation is in good coherence with our expectation. The strangeness production is measured in a form of ratio between various strange to non strange particles. The particles carrying strange quarks are not in complete chemical equilibrium. There appears to be an additional suppression [8] which is expressed as

$$\lambda\lambda_s = \frac{s\bar{s}}{\frac{1}{2}(u\bar{u}+d\bar{d})}$$

The observed enhancement as one goes from nucleon-nucleon to nucleus-nucleus collision can be explained by a concept called phase space suppression. Strange particles produced in "small systems" like proton-proton are suppressed due to exact conservation of quantum numbers.

The QGP hypothesis seen via means of strangeness flavour observables basically stands on three pillars. A large number of ultra-relativistic collision experiments have successfully validated them. It can be explained as:

a) The matter –antimatter symmetry is expected for the baryon and antibaryon particles:-The WA97 [9] experiment showed a highly unusual symmetry between the two as witnessed from a detailed study of transverse mass spectral shape.
b) An enhancement of (multi)strange baryon and antibaryon with increasing strangeness content. WA97, NA49 and WA85 experiments [9] successfully observe the enhanced yields.
c) A strong enhancement in strangeness flavour yield per reaction participant (baryon), with the effect being strongest at the mid-rapidity region. Experiments [9] NA35, WA85, WA94 and NA44 involving Sulphur induced reactions confirm strangeness enhancement at mid-rapidity. The NA52 experiment occurs all of a sudden as the centrality rises with the size of participating nucleon rising above baryon number B=40-50.

The understanding of strangeness production in heavy-ion experiments has far-flung implications for several exotic reasons such as the possible existence of multi-quark hadrons such as H-dibaryon [10], evident proof of Witten's conjecture which requires hypothesized stability of strange matter and the possible existence of strangelets [1].

3. Strangelet production as a consequence of strangeness distillation and related phenomenon

Multiquark states containing u and d quarks ought to have a mass larger than ordinary nuclei. If this is not so, normal nuclei would not be stable. However, for droplets of SQM (strangelets), the situation is different, which contain almost equal amounts of u, d and s quarks. Strangelet detection has so far eluded scientists, be it on the cosmological front or during heavy-ion collisions but their observational expectancy is quite high. A significant flux of cosmic-ray strangelets is expected from collisions of binary compact star systems containing strange stars. These binary star systems collide after inspiral due to the loss of orbital energy in the form of gravitational radiation.

During high energy collisions or formation of hot QGP created in the early Universe, equal amounts of strange and antistrange quarks are produced with strangeness saturating the phase space in baryon rich environment after equilibration. Also, it is difficult to assemble non-strange quarks into non-strange matter or antimatter particles. Therefore, the study of strange anti-baryons could reveal as to how the early universe evolved into its present form. Furthermore, at finite baryon densities, distillation process works separating strangeness from antistrangeness. The scenario assumes a first order phase transition, predicting a relative time delay between the production of strange and antistrange particles. The possibility of separating strange quarks from its antiquarks leads towards a late stage of phase transition to an extensive enrichment of strange quarks in the QGP phase. This leads to a possible enlargement of strangeness mass-function in remaining droplets. This quark matter with net finite strangeness might be absolutely stable or metastable state of strongly interacting matter at zero temperature and at some finite chemical potential with the $s/\bar{s}$ quark ratio greater than 1. These blobs of multistrange quark matter i.e. "strangelets" are probably the only form of quark matter not subject to rapid decay and can decay only via weak interactions [1,11]. Practically, if strangelet does exist in principle, it has to be regarded as a stable, cold and bound manifestation of the remnants of the originally hot QGP phase. , A distinguishing feature of strangelet would be its unique charge to mass ratio [12] lying in the range $-0.5<Z/A<0.15$with a lifetime exceeding 10^{-6} sec. It is worth noting that the accumulation of s-quarks in the plasma phase grows with decreasing plasma volume. Also, from strangelet computations, it has been found to be absolutely stable for only large A>10. However metastable strangelets could exist but for smaller values of A.

During the hadronization process, the net baryon number (A_B) decreases and the s quark chemical potential increases from 0 to several tens of MeV, leading to an increase in strangeness fraction

$$f_s = (N_s - N_{\bar{s}})/A_{tot}.$$

The triply strange and otherwise rarely produced particles Ω(sss) and $\bar{\Omega}(\bar{s}\bar{s}\bar{s})$, which are also the heaviest stable hadrons (M=1672 MeV) serve as best signatures for deconfinement. The microscopic evolution study of Ω and $\bar{\Omega}$ yields reveal that they decouple from the hadron background earlier as compared to all the other hadrons [13,14,15]. This early chemical freeze-out significantly influences their statistical yield. Say for example, in order to increase the yields by a factor of 2, the freeze-out would occur at T_Ω=150 MeV rather than T_f=143 MeV. Since the temperature keeps dropping after the fireball explosion, higher freeze out temperature implies an early production. The experimental yields of Ω and $\bar{\Omega}$ are far greater than as expected theoretically. This may probably be due to the fact that their production cannot be explained by single stage freeze out model [16]. A strange fact to be observed here is that all other particles are consistent with the single freeze out condition.

The heavy-ion collisions makes it possible to create an environment which is favourable the formation of metastable exotic multihypernuclear objects (MEMOs) whose presence signifies a conservative estimate for the production of temporarily present QGP state. MEMO's are nuclei containing strange baryons, where the conventionally present neutron is replaced by a strange particle (for eg. Λ hyperon)in scattering experiments with pions or kaons. Some of the properties of a MEMO are seemingly identical to that of the strangelets and their almost identical microscopic structure gives rise to a vision that both states are co-related and overlap on each other. They have nearly the same average baryon density which is approximately $3\rho_0$. The charge $|Z|$ is also nearly the same. It may however be noted that a MEMO is only bound in the order of E_B/A~10MeV, whereas the strangelet may be bound from10-200 MeV. A MEMO would decay into a strangelet if it is energetically more favourable to do so. The lifetime of a MEMO is expected to be the same as the lifetime which is approximately 10^{-10} seconds.

4. Strange quark matter

The asymptotic freedom feature guarantees the quarks and gluons to be the ground state of QCD at high temperatures, but gives no information about the ground state at low temperatures. However, at low temperatures the strange quark matter turns out to be the most problable candidate for the ground state. SQM is considered to be a hypothetical state of matter [17,18] with typical properties such as low charge to mass ratio, high level of stability and large mass range. The ordinary matter like the protons and neutrons are primarily made up of the “up” and the “down” quarks. It has been speculated that these two quarks when melded with a heavier strange quark, forms matter which is capable of an independent existence and could grow far more massive than ordinary atoms and is called SQM. The very discovery of SQM would lead to an understanding of behaviour of freely interacting quarks which until now have defied independent existence. Also, existence of SQM could provide a possible explanation of a large part of the non-observable mass of the Universe in certain cosmological models. SQM may be composed of equal amounts of delocalised u, d and s quarks and a possible small ratio of electrons. Multiquark states consisting of only u and d quarks will have mass larger than normal nuclei. However strange mutiquark [19] clusters are more compressed than ordinary nuclei and may exist as long lived exotic isomers of nuclear matter within the neutron stars.

It has been theorized that the hypothetical SQM at zero temperature and equilibrium could be far more stable than atomic nuclei. The hypothesis of stability of SQM is visualized by the following arguments [20]:-

a) The weak decay of an s quark into a d quark would be forbidden or suppressed because the lowest single levels are occupied.

b) SQM has a small positive charge to mass ratio and neutrality is attained by the existence of electrons.

c) The strange quark mass is lower than the Fermi energy of the u or d quark in SQM droplet. Thus, opening of new degree of freedom allows for a re-arrangement of energy and this causes the lowering of energy per particle.

The physics of SQM has an excessive possibility for an intimate relation with quark-gluon plasma state. The only way to detect transient existence of QGP is through the experimental observation of its exotic remnants, like the formation of SQM droplets. If SQM exists, it can be in the colour superconducting state [21,22,23,24]. It occurs because of the strong interaction phenomenology. The strong interaction among quarks is very attractive in some channels. Thus, it is evidently expected that pairs of quarks form Cooper pairs quite readily. Each quark carries a particular quantum number, therefore pairs of quarks are not colour neutral. The local colour symmetry is thereby broken and the resulting condensate will be called a colour superconductor. Since the quarks come in three different colours, different flavours and different masses, the phase diagram of such matter is expected to be very complex. The SQM may be in colour flavour locked (CFL) phase, two flavour superconducting (2SC) phase and a gapless CFL phase. Strangelets made up of CFL strange matter obey charge to mass relation of $Z/A=A^{-1/3}$. For ordinary SQM, Z/A would be approximately constant for small baryon number A and $Z/A=A^{-2/3}$ for large A [3,25,26].

5. Stability of strange quark matter and its possible consequences

Some strong interaction models, most considerably the MIT bag model, favour the absolute stability of SQM for certain ranges of parameters [1,19,27]. For nuclear matter, E/A= 930 MeV, a simple estimate shows that for strange quark matter described by the MIT bag model($E/A=4B\pi^2/\mu^3$), with bag constants of $B=57\ MeV/fm^3$ and $B=85\ MeV/fm^3$ would place the energy per baryon of such matter at E/A=829 MeV and 915 MeV respectively, which clearly depicts stability with respect to nuclear matter. The absolute stability or quasi-stability of SQM grants that SQM produced in the early moments of the Universe at T~100 MeV could exist as heavy isotopes with low charge and unusual high mass. The expected properties of SQM makes it easier to accelerate and less prone to energy losses than protons or ions. Also, strangelets are evident candidates for highest energy cosmic rays.

The absolute stability of SQM can bear some intriguing consequences. This may prove to be an evident explanation for the cold baryonic dark matter in the Universe [1,28]. The absolutely stable SQM could be a possible dark matter candidate but there is actually no solid proof of it. It is speculated that nuggets of SQM could have escaped during the cooling of the early Universe when phase transition from deconfined to confined matter was taking place. It is believed that these nuggets carry most of the small excess of baryon number of the Universe. Neutrinos, mesons or baryons can be emitted from these nuggets and basically carry away the heat and entropy. For an absolutely stable ground state, the hot nuggets would cool down further and instead of complete hadronization might settle into these new states. This would evidently solve the dark matter problem.

There are some other possible consequences of the absolute stability of strange quark matter. The stable pre-quark matter phase might also explain the formation of massive black holes in galactic centres, formation of galaxy clusters and the possible source of γ ray bursts (GRBs). Some of the most promising sources of GRBs basically considered involve merging of neutron stars to black hole, collapsing of black holes and collapsing compact stars. Also, the study of SQM [3] in supernovae showed that this possible subnuclear energy source is more than sufficient to contribute to the explosion and the observed neutrino emission [29] of SN1987A can be explained through this operating scene. The idea that neutron matter is converted in SQM in the centre of neutrons is widely explored [30,31,32,33,34,35,36]. For the formation and propagation of SQM to proceed, its physics demands observational evidences of GRBs to display non-isotropic γ ray emission [37] i.e. a jet like geometry, where conversion of neutrinos to γ's proceeds through the reaction

$$\nu\bar{\nu} \rightarrow e^{+}e^{-} \rightarrow \gamma\gamma \quad \text{(under the presence of moderate magnetic field}\sim 10^{13}\text{ G)}$$

There are even some seismological evidences for the presence of SQM. In 1984, Nobel Laureate, Sheldon Glashow brought forward a suggestion that physicists should team up with seismologists in search of traces of SQM, which have quite a possibility of passing through the Earth at supersonic speeds with the seismic signature expected to be distinctively different from ordinary Earthquakes. The SQM is immensely dense such that a piece of the size of human cell would weigh a tonne and it was speculated that one tonne spec would release energy of 50 kilo tonnes of nuclear bomb and the spread would be along its entire path through the Earth with a distinctly unique seismic signal which would be straight line with estimated speed of about 400km/sec (40 times the speed of seismic wave).

In the year 1993, a group of researchers [38] from the Southern Methodist University, US began looking for seismic events possibly caused by strange quark matter. They searched the world's seismographic records for the so called "unassociated events" which had no association with traditional seismic disturbances such as earthquakes.

One event occurred on 22nd October, 1993, when something entered Earth off Antartica and exited from south of India 0.73 seconds later and the event was monitored at seven stations in India, Australia, Bolvia and Turkey. Another event occurred on 24th November, 1993, when some object entered south of Australia and exited the Earth near Antartica 0.15 seconds later. This event was recorded at nine monitoring stations in Australia and Bolvia. Some scientists are very sceptical over the fact that these seismic disturbances actually correspond to SQM. Thus, we can say that although there is no direct proof that these two events correspond to SQM, but this is the only convincing explanation which physicists could find till date.

6. Strange stars

The Bolder Witten hypothesis formulated by A. R. Bodmer [19] in 1971 and revived by E. Witten [28] regards that SQM could be the true ground state of matter. One of the most evident consequences of this hypothesis is the possible existence of a new class of compact stars, completely made up of SQM, which are called strange stars. Their existence hinges on the assumption that SQM is more stable than ordinary nuclear matter. However, the strange matter hypothesis does not conflict with the existence of strange stars in the Universe. The masses, cooling behaviour, radii, spin evolution and surface composition of compact stars are well affected by the strangeness carried by mesons, hyperons, H-dibaryons and SQM. Strange stars, which are self bound objects are expected to be gravitationally stable and for most part resemble the conventional neutron stars. Strange star modelling by a number of physicists [39,40] showed that they have a typical mass (of~1 to $2M_0$) and radius (of~10kms) and adheres to the possibility that pulsar like stars which were thought to be neutron stars could actually be strange stars.

The masses and radii of strange stars are quite similar to those of the neutron stars, so it becomes difficult to single out signals which correspond to quark matter in pulsar like stars. However, the cooling behaviour of strange stars is quite different from that of the neutrons stars. Strange stars cool much faster than neutrons stars [41], but the analysis is virtually possible in about 30 years after their births [42]. The notion that neutron stars are the endpoint of stellar evolution had a strong hold. If strange stars exist in nature, they are expected to be far more denser than any neutron star. In fact, these quark stars are not dense enough to be black holes, but they are too dense to be anything else.

There are indications that certain neutron stars could in fact be strange stars. It is however quite difficult to distinguish between the two but there may still be effective ways to do so. The two can be distinguished from their approximate mass-radius (M-R) relations. The strange stars obey the $M \alpha R^3$ dependence in contrast to $M \alpha R^{-3}$, for the case of neutron stars. The strange stars can thus have a much smaller radii in comparison to neutron stars. Also, the minimum rotation periods of strange stars are much smaller than the neutron stars. The bulk viscosity [43] of strange matter is higher than that of neutron matter though their shear viscosities are similar. Therefore, strange stars have smaller period of rotation and their higher viscosity prevents them from developing rotation mode instability [44]. Another distinguishing factor is between the surfaces of bare strange stars (BSSs) and neutron stars. The surfaces of BSSs are characterized by strong electric fields, strong binding of particles and sudden change in density from $4x10^{14}$ g/cm^3 to approximate zero to about 1 fm. In contrast to ordinary neutron stars, strange stars cause higher frequencies in the gravitational wave signal before 'touch down' due to being more compact in the cases studied by authors.

On the experimental front, there has been some identification of certain stellar objects which tend to correspond to strange stars. The Chandra X-ray telescope, in collaboration with the Hubble Space Telescope studied two objects that were thought to be neutron stars. The object RXJ1856 in the constellation Corona Australis is about 400 light years from Earth. X-ray data from RXJ 1856 was analyzed and the scientists found it too small to be a neutron star. The other object in constellation Cassiopera is about 10000 light years away. Scientists were unable to detect the X-ray radiation which was expected to be emitted from the hot surface of 3C58. This indicated that the temperature of the object is far below that of a neutron star and this was speculated to be a strange star. Another strange star candidate is SAXJ1808.4-3658, which was discovered by Beppo SAX satellite. SAXJ1808.4-3658 is a X ray millisecond pulsar with pulsation period of 2.49ms. Its observational mass-radius (M-R) relation was compared with theoretical M-R relations for traditional neutron stars and strange stars [45]. The data was in coherence with that for the strange stars and this suggested that SAXJ1808.4-3658 could be a strange star.

The neutron stars seem to be the most credible sites in the Universe, where strangeness bearing matter with a strangeness bearing matter with a strangeness to baryon ratio, f_s=-S/B~1 may exist. Neutron stars are likely to be strange in the interior. Strangeness can exist inside the neutron stars, both in confined form (hyperons and kaons) or in deconfined form(strange quark matter). Ordinary SQM in bulk is believed to exist only in the interior of neutron stars where the pressure is quite high, so that neutron matter melts into its quark substructure [3]. The core of the neutron star is not very promising place for matter to consist of individual hadrons because density of the core rises to 10 times the normal nuclear density. A neutron star will be called a hybrid star when it has a quark matter core in the deep interior and baryonic matter in the outer region. Also, a newly born hot strange star with strange phase can have more mass than a cold one so that the cooled neutron star collapses into a black hole.

Some physicists believe that if a strangelet will penetrate a neutron star, it will convert it into a strange quark star in a time scale of minutes [46]. This notion is based on the assumption that if SQM is the ground state of matter, a strangelet will absorb free neutrons and then convert them into strange quark matter. Also, it is speculated that massive stars with SQM seed in the core will give birth to a strange quark star and not a neutron star. There is a lot of work being pursued on the possible phenomena related to strange stars, such as explosive conversion of neutron stars to strange stars [46], collapse of neutron stars to quark stars [47], generation of secondary shock wave in supernova explosions [48,49]. A fraction of strange quarks stars must participate in binary mergers with other compact objects in which some SQM is injected into the galactic disk.

6.1 Strange dwarfs

Strange dwarfs are speculated to be small and light white dwarfs with a strange star core [50,51,52]. The radius is smaller than traditional white dwarfs. Several stars such a GD 140, G156-64, EG 21, EG 50, G181-B5B, GD 279, WD 2007-303, G238-44 are unusually compact and are possible strange dwarf candidates.

7. Bag model parameters and the strange star phenomenology

The theory of strong interactions pose a great deal of intrinsic difficulties and thereby the quark phase is described in terms of models, with the MIT bag [53] model being the most popular. In this section, the bag model parameters have been utilized to study strange stars with a crust and strange dwarfs. Two sets of bag model parameters have been used to determine their equations of state. These basic parameters characterising our analysis are the bag constant B, which reflects the vacuum pressure in the volume occupied by the quarks; m_s, the mass of strange quarks; α_c, the quark-gluon coupling constant; n_s or n_{min}, the surface density and ε which is the mean energy per baryon. The mean energy per baryon essentially has negative minimum and depends upon the baryon concentration for the strange stars and ensures that SQM is bound. The impact of these parameters upon the stability of SQM was determined in the pioneering work carried out by Farhi and Jaffe [1]. Realistic ranges of these parameters have been used [54], which generalize the phenomenological and theoretical data of hadron physics.

By integrating the Tolman-Oppenheimer-Volkov equations (relativistic equations of steller equilibrium) [55], the main parameters of spherically symmetric superdense stars were modelled. The TOV equation being

$$\frac{dP(r)}{dr} = -\frac{G\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[m(r) + \frac{4\pi r^3 P(r)}{c^2}\right]}{r^2\left[1 - \frac{2Gm(r)}{rc^2}\right]}$$

where $m(r) = \int_0^r \rho(r')d^3r'$

is the mass of the star within radial coordinate r and P(r) is the pressure. ρ(r) is the neutron drip density. The radius R of the star is defined by

$$R[P(R)=0]$$

and the total mass M of the star (the gravitational mass observed by a distant spectator) is given by

$$M = m(R) = \int d^3r\rho(r')d^3r'$$

The solutions of the TOV equations fall into sequences characterized by two parameters:-the central density of the core ρ_c and the inner density of the crust ρ_{cr}. The maximum density of the crust is limited by the neutron drip density, above which neutrons would gravitate to the strange core and be converted to quark matter. For a particular equation of state and each pair of such parameters, there is a unique stellar structure with a particular mass and radius. For an entire range of realizable core densities ρ_c and three limiting values of crust densities ρ_{cr} , we have used tabulated data [56] on mass, radius, core mass and core radius for a sequence of stars ranging from compact strange stars to extended strange dwarfs constructed out of the strange quark matter. These parameters were determined corresponding to configurations for both maximum and minimum masses of strange stars with crust and for maximum masses of the strange dwarfs. Furthermore, we have also calculated the gravitational redshift Z_S and apparent radius for the entire sequence.

Two models have been scrutinized where the first model describes normal matter in *Ae*(degenerate electrons) phase. We have used the tabulated data on the Baym-Pethick-Sutherland equation of state [57] matched to Feynman-Metropolis-Teller equation of state [58]. The second model corresponds to strange quark matter, for which the MIT bag model has been used. The two sets of the realistic bag model parameters of the equations of state used [56] for the above mentioned models are listed in Table 1. The three different values of crust density i.e. $4.3*10^{11}$(= neutron drip density), 10^{10} and 10^9(gm/cm^3) have been employed for tabulation of data of various basic parameters of the sequence of strange stars(with a crust) and strange dwarfs.

Table I:- Parameters of Equation of State of Strange Quark Matter

	B (MeV/fm^3)	m_s (MeV)	α_c	n_{min}(fm^3)	ε
Model 1	50	175	0.05	0.257	-64.9
Model 2	60	175	0.05	0.296	-28.6

In this section, we have utilized the calculated integral parameters for strange stars and strange dwarfs for the purpose of analysis. This is done by plotting them with the aim of pinpointing peculiarities of the strange star behaviourism in contrast to that of neutron stars and also comparing the strange dwarfs with their non-strange analogs, i.e. ordinary white dwarfs. Viable differences between them are clearly visible.

The M-R plots for compact stars have been actively studied since a long time. Their peculiar behaviourism help in differentiating the strange stars from the neutron stars. Figures 1and 2 show the M-R plots of strange stars under the two models and for the three different values of the crust densities ρ_{cr}. The observed pattern is in coherence with that of other authors [59]. It is evident that both the models exhibit the fact that the maximum mass of the strange stars with a crust is essentially independent of ρ_{cr}, whereas the minimum mass of configuration is very sensitive to the magnitude of this parameter.

The M-R plot for the neutron stars is depicted in Figure 3. On comparing these three figures, we can clearly observe that the pattern of variation of mass with radius is different for the strange stars and their non-strange counterparts, i.e. the neutron stars. Thus, we can say that the M-R plots serve as a basic comparative feature for differentiating these two types of stars.

We determined the gravitational redshift Z_s at the surface of the star. This is a directly observable parameter and thus the experimental data can be compared with its theoretical counterpart. The expression for redshift Z_s is

$$Z_s = (1 - \frac{2GM}{Rc^2})^{-1/2} - 1$$

In figures 4 and 5 we have plotted redshift as a function of mass for strange the two models corresponding to three different crust density values. Model 2 depicts abrupt changes in Redshifts with respect to mass for the three values of the crust density, which is in contrast to that of model 1. Figure 6 shows the plot between Z_S and mass for the neutron stars. The gravitational redshift projects out as a basic comparative parameter in differentiating these two types of stars. The derived values of Z_s for strange stars ($Z_{s\ min}$=9.55*10^{-6} to $Z_{s\ max}$=0.48) corresponding to different values of mass are lower than those for neutron stars ($Z_{s\ min}$ =8.34*10^{-4} to $Z_{s\ max}$ =0.649). This result is in coherence with that of other authors [57].

In order to determine the differences between the strange and white dwarfs, we have used the highest value of the crust density i.e. ρ_{cr} =4.3*10^{11} and comparison amongst various parameters for the two is performed for the same masses in the interval from M=0.02$M_{\odot}$ to 0.96 $M_{\odot}$. It is worth noting that the integral parameters for the ordinary white dwarfs are those obtained from Feynman-Metropolis-Teller equations of state [58]. When the densities of nuclear matter crust fall below the critical limit of the neutron drip density, there is quite a possibility that there could exist ordinary white dwarfs which envelop a strange quark core.

Similar analysis for strange and white dwarfs (both for the same mass values) was performed under the Model 1. The M-R plots clearly depict visible differences in their corresponding variations and this serves to be a basic analysing and differentiating parameter. Figure 7 clearly depicts that for mass values less than 0.2$M_{\odot}$ the two can be easily differentiated as for the same mass values, the white dwarfs have very high radii in contrast to that of strange dwarfs. This difference is substantial and therefore the compactness of strange dwarfs leads to lowering of surface luminosities in comparison to that of the ordinary white dwarfs.

The plots of core density (Figure 8) as a function of mass for strange and white dwarfs also serve as a basis of comparison between the two. The directions of variations of core density are opposite and this feature projects out the characteristic difference between them. The stable branch of ordinary white dwarfs encounter an exponential increase of core density with the mass, whereas, the strange dwarfs show an exponential decrease of core density for same mass values.

The surface redshift Z_S values were calculated for both the strange and white dwarfs, but the range ($1.29*10^{-6}$ to $3.97*10^{-4}$) is almost the same for the two and thereby the plot (Figure 9) between the redshift and mass for the two show similar behaviourism. Thus, Z_s does not prove out to beneficiary as a comparative parameter.

Compact stars are relativistic objects and their stellar surface radiates photons. Detection of photons emitted from the surface of compact stars of known distance can result in the determination of the apparent or the radiation radius which is defined as

$$R_{apparent} = R/(1-2GM/(Rc^2)^{1/2}$$

where R is the circumferential radius or the true radius of the star. Because of sizable space time curvature close to the compact star, there is difference between the true radius, which is the radial coordinate of the stellar surface in Schwarzchild metric and the apparent radius, as determined by a distant observer studying radiation from the surface of the compact star. In Figures 10 and 11, we have plotted mass versus apparent radius for a sequence extending from strange stars with crust to strange dwarfs for the two models. The sequence starts at the strange stars and terminates at the white dwarfs. The central density decreases monotonically through the sequence being maximum in the compact configuration.

Furthermore, in figures 12 and 13, we have also incorporated the M-R plots for core values and exponential variation of mass with radius is observed for both the models. Figures 14 and 15 depict the variation of logarithm of core density with respect to radius of the core for the two models. Both the models display similar behaviourism. For radius up to 7 kms the core density remains almost constant and variates considerably between 8 to 11 kms of core radius. The different values of crust density do not affect the pattern of variation.

8. Multiquark states

Quantum Chromodynamics, the fundamental theory of strong interactions, in principle does forbid the isolated existence of single quarks but does not deny the existence of larger hadronic particles, called multiquark states. There is a possibility of existence of states with more than three quarks, that is quark composites other than hadrons (two or three quark states) could be known in nature and basically no physical principle excludes their isolated existence. The earliest being the H-dibaryon (H=[ud][ds][su]), which is a novel particle that could be pertinent to the composition of neutron star matter. It is a doubly strange particle and is a six-quark composite. There is a high level of possibility that this particle could turn up as a possible candidate for a strongly bound exotic state. The Λ particles constitute an integral part of the neutron matter and two Λ hyperons could combine together to form an H-dibaryon. This procedure would therby lead to the formation of H-dibaryon matter. The requisite density for this process to occur is somewhere above ~ $4n_0$. It is however worth noting that this H-dibaryon matter appears to be unstable against compression and this could lead to the conversion of neutron stars into the hypothetical strange quark stars. Furthermore, neutron star interiors are postulated to contain pentaquarks having strange quarks. Their presence reduces the overall pressure decreasing the maximum mass of quark stars.

FIGURE 1

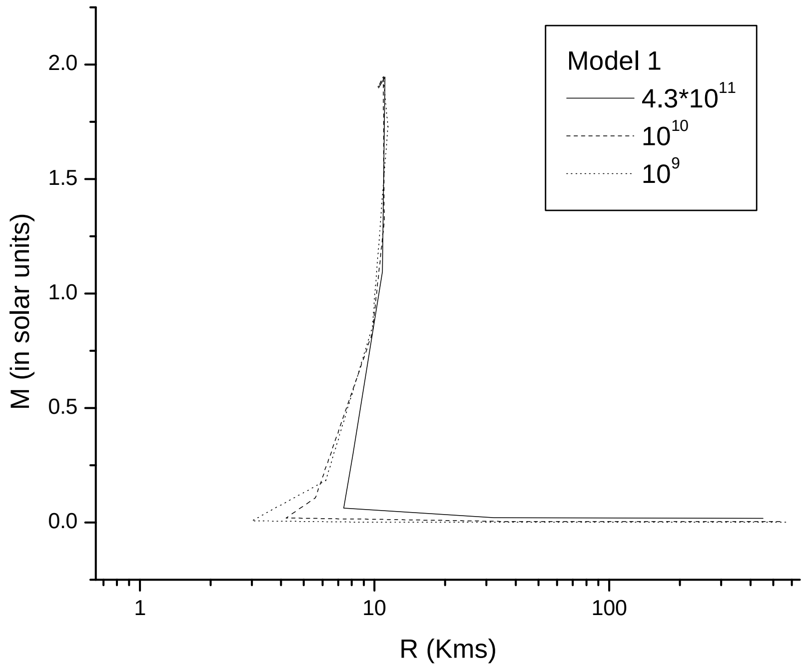


FIGURE 2

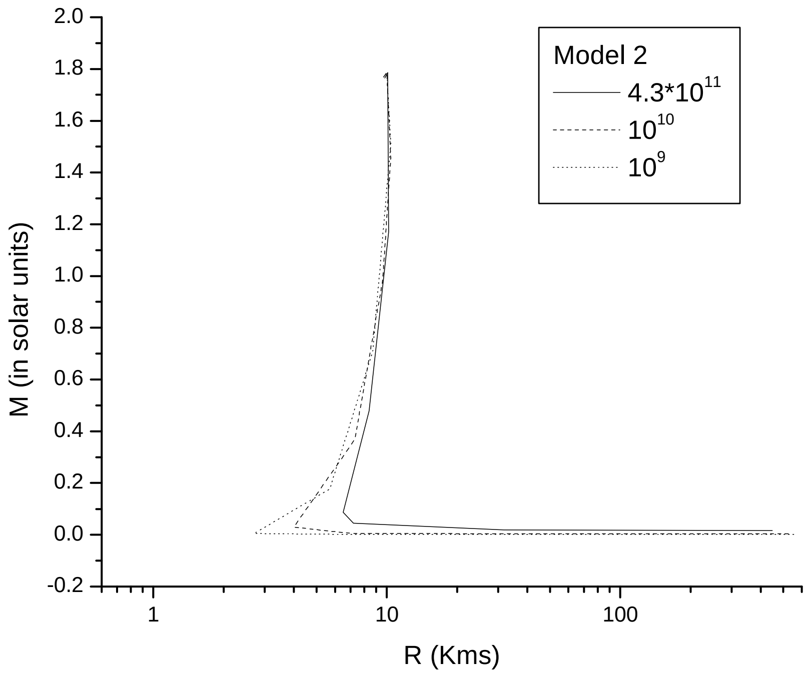


FIGURE 3

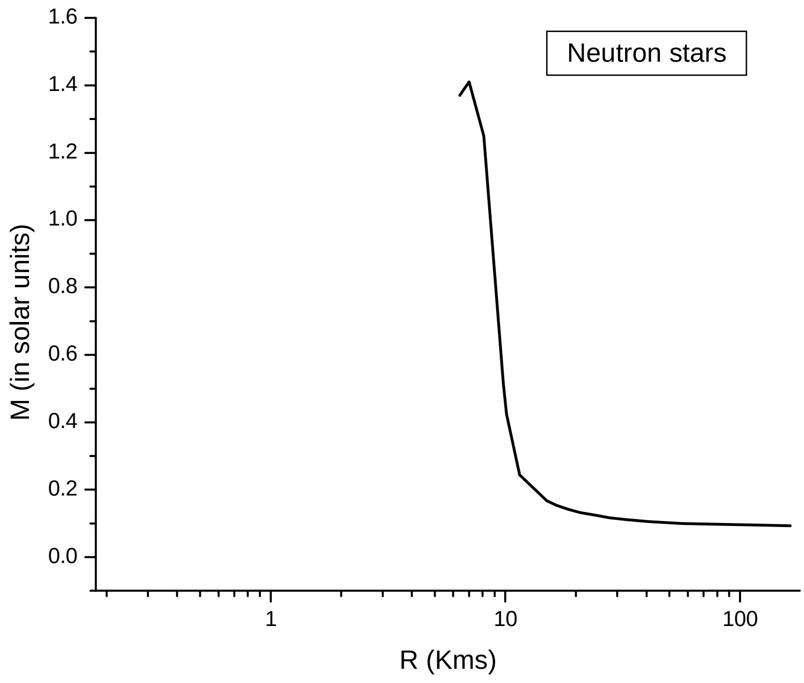


FIGURE 4

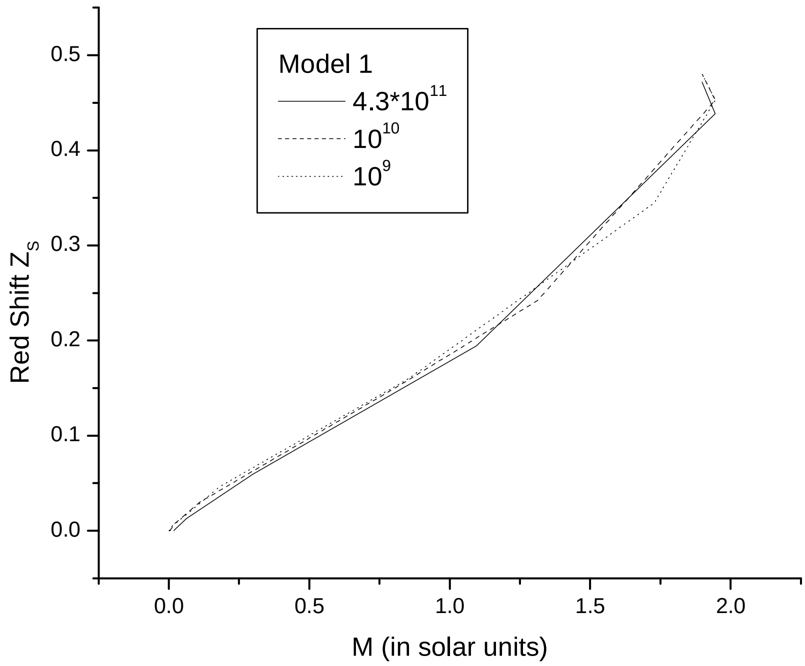


FIGURE 5

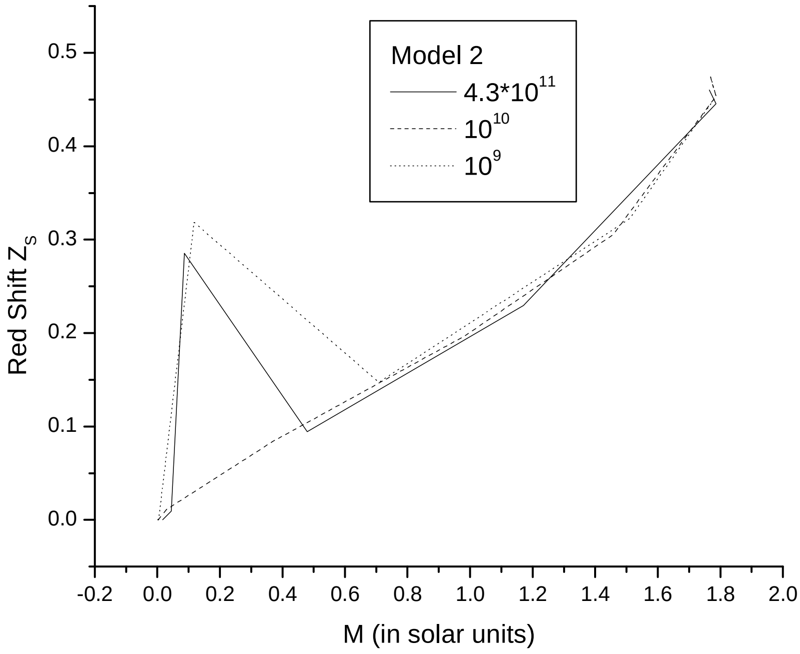


FIGURE 6

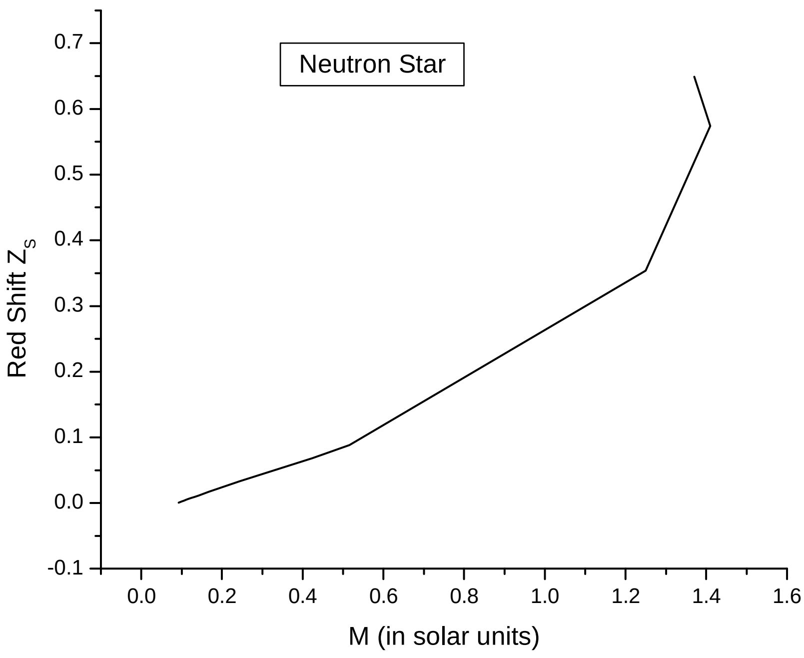


FIGURE 7

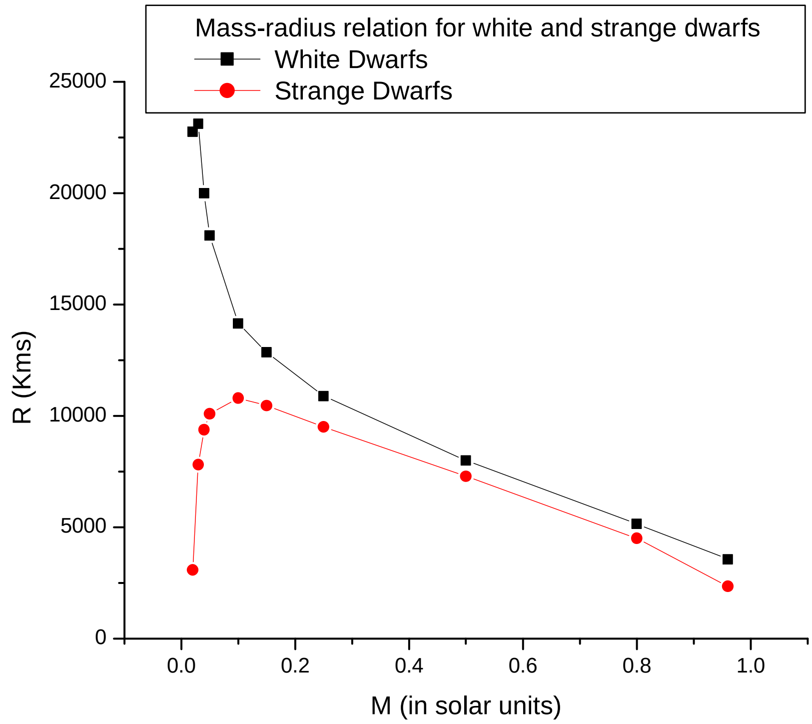


FIGURE 8

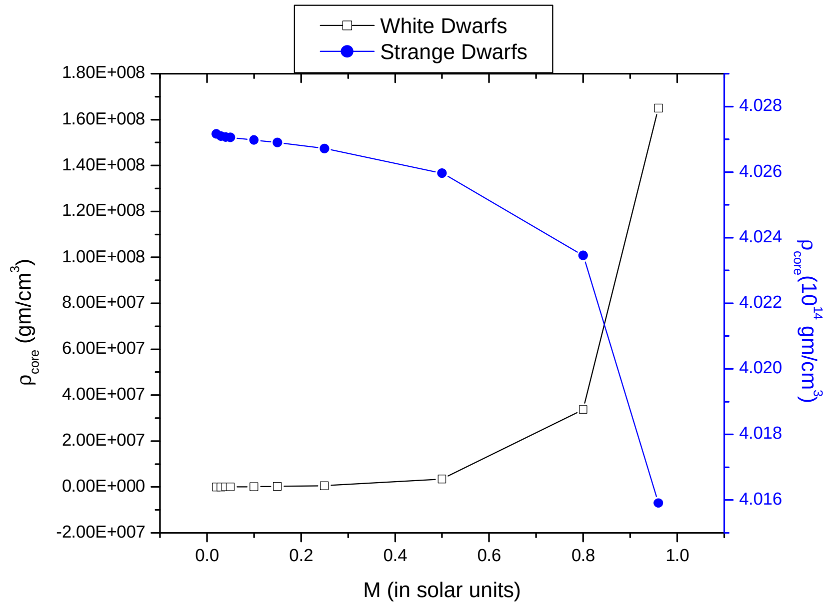


FIGURE 9

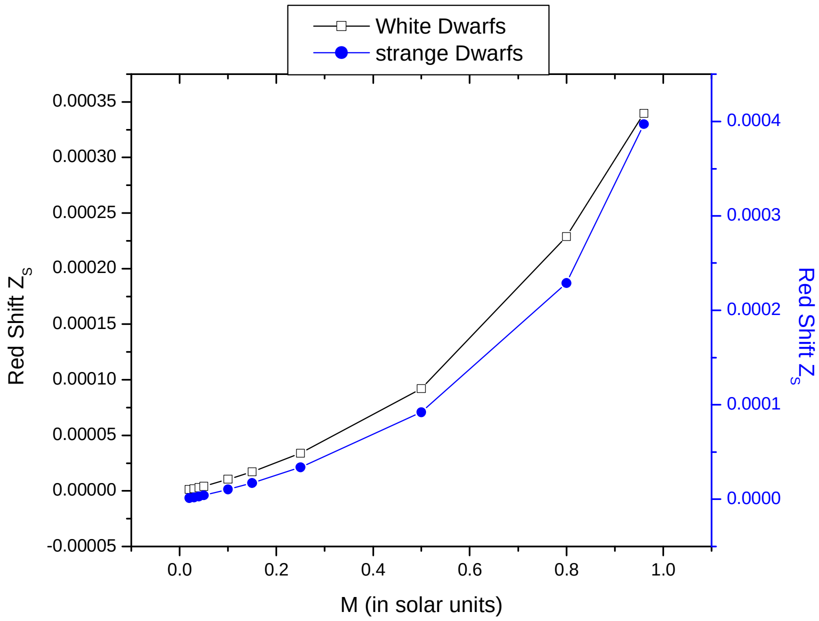


FIGURE 10

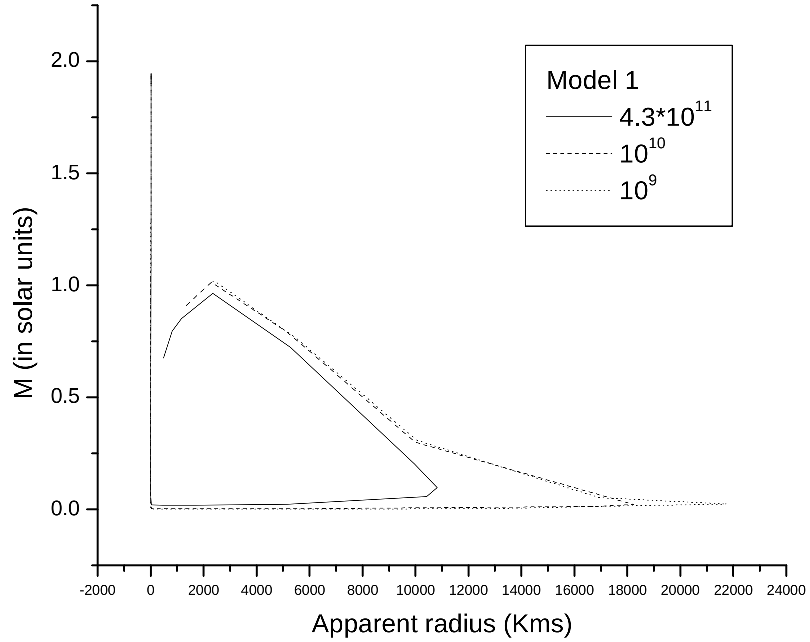


FIGURE 11

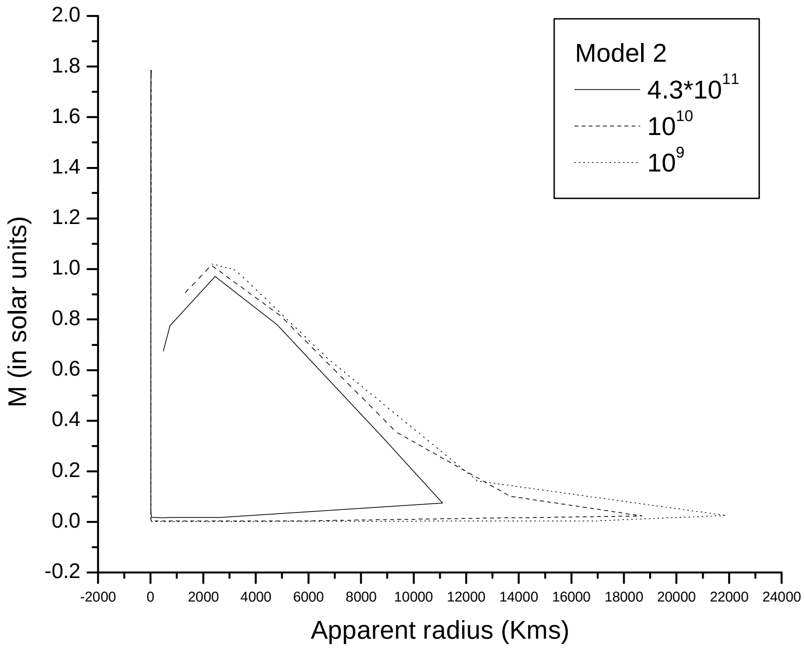


FIGURE 12

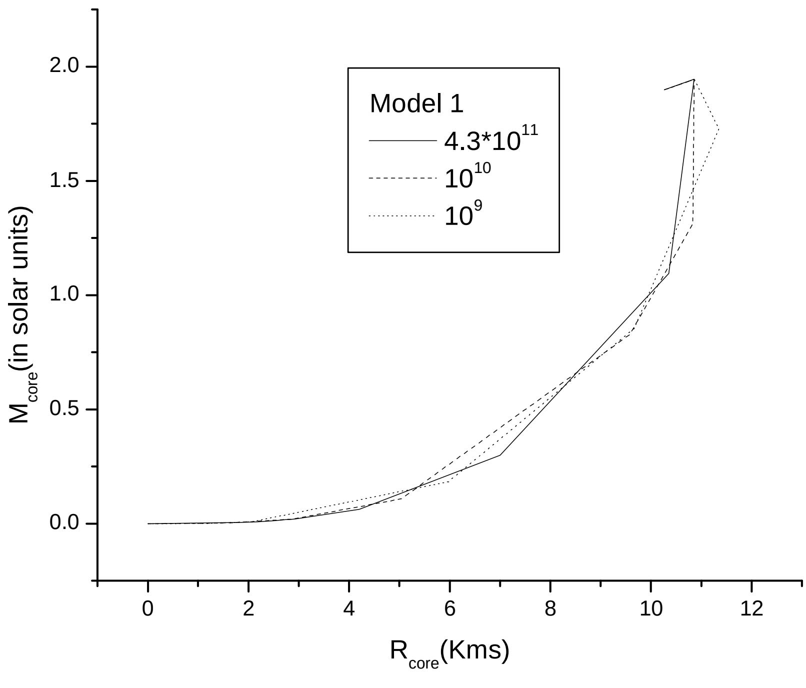


FIGURE 13

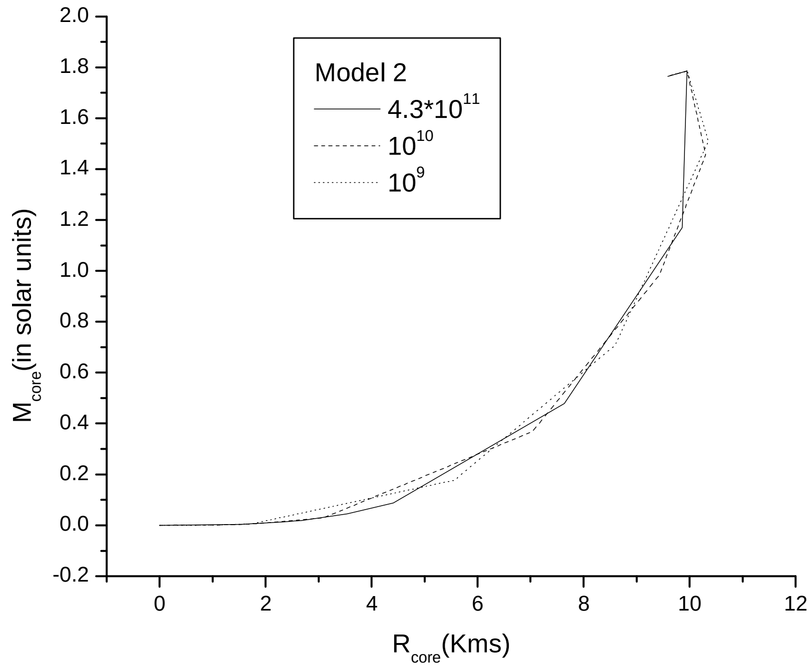


FIGURE 14

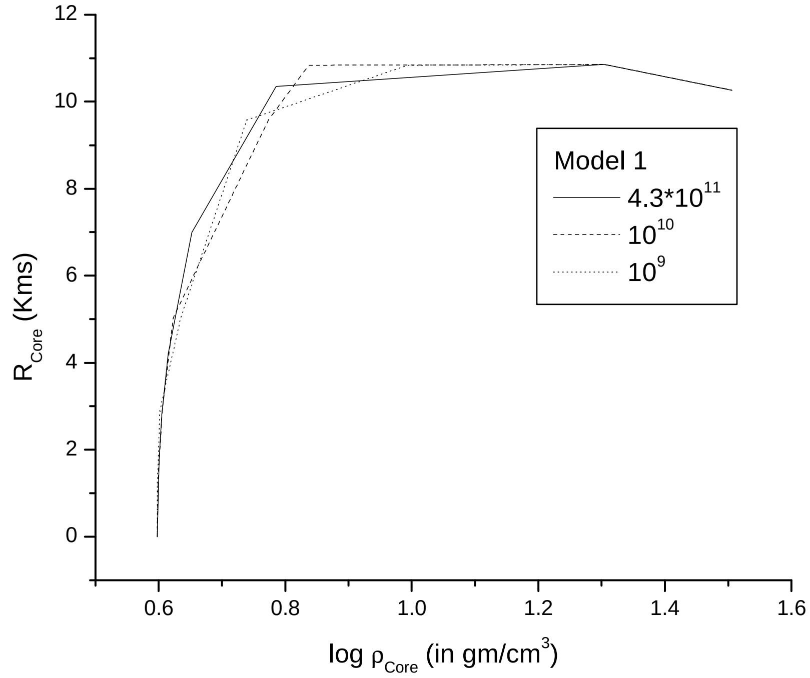
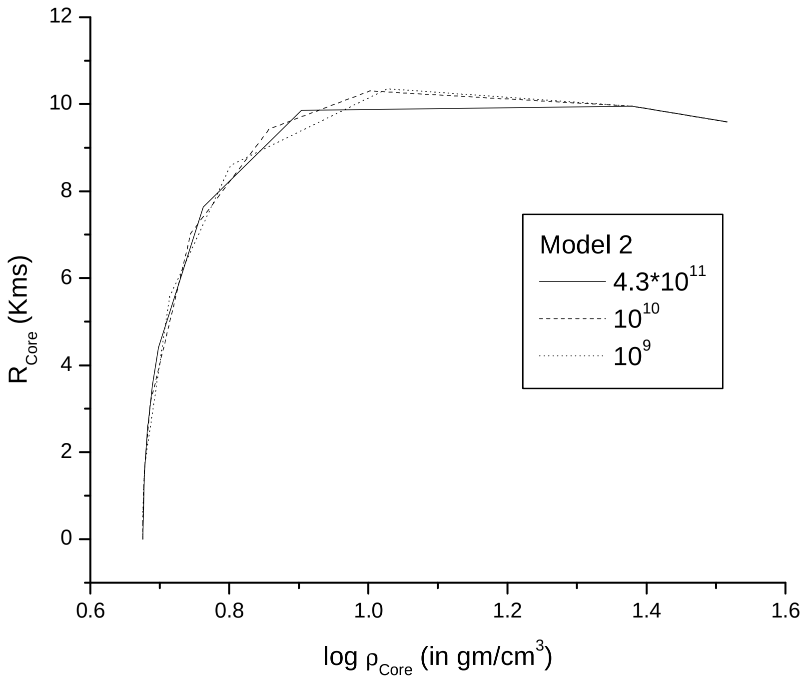


FIGURE 15



CONCLUSION

It is quite evident that the strange quarks implicitly as well as explicitly affects physics at the astrophysical scale. Cause of contributions from the strange quarks is mainly attributed to their strange behaviour which is basically due to the fact that strange particles are produced copiously by strong force energy and decay through weak interactions. This long decay time makes them easy to detect. The other contributing factor is the strange quark mass, which being equivalent to the temperature or energy at which hadrons dissolve into quarks. The absolute stability of SQM and it being the true ground state has some intriguing consequences and could explain the physics of deconfinement at low temperatures. It adheres to the possibility that strange stars if detected, could be the endpoint of stellar evolution. There is an evident possibility that some neutron stars could be strange stars and even the neutron stars could be strange in the interior. Even our study based upon the bag model parameters gives boost to fact that strange stars and strange dwarfs show observational differences from their non-strange counterparts which are the neutron stars and strange dwarfs respectively.

Furthermore, the formation of black holes, source of ray bursts and SQM being a possible dark matter candidate could be consequences of SQM stability. A clear enhancement of strange particle production in heavy ion reactions is observed, with production being magnified from nucleon-nucleon to nucleus-nucleus collisions and strong enhancements for doubly and triply strange baryons.

Acknowledgement

One of us (NH) gratefully acknowledges the RFSMS (Research fellowship in science for meritorious students) scheme of University Grants Commission, New Delhi, for financial support.

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