Observational constraints on quark matter in neutron stars

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Abstract We estimate the constraints of observational mass and redshift on the properties of equations of state (EOS) for quark matter based on the quasiparticle description in the compact stars. We discuss two scenarios: strange stars and hybrid stars. We construct the equations of state utilizing an extended MIT bag model taking medium effect into account for quark matter and relativistic mean field theory for hadron matter. We show that quark matter may exist in strange stars and the interior of neutron stars. The bag constant is a key parameter that affects strongly the mass of strange stars. The medium effect can lead to the stiff hybrid-star EOS directing to the pure hadronic EOS due to the reduction of quark matter, and hence the existence of the heavy hybrid stars. We find that the intermediate coupling constant may be the best choice for compatibility with observational constraints in hybrid stars.

Key words: dense matter — gravitation — stars: neutron — stars: rotation — stars: oscillations

1 INTRODUCTION

The interiors of neutron stars contain matter at very high densities that are a few times and even up to more than ten times the density of ordinary atomic nuclei. This could provide a high-pressure environment in which numerous subatomic particle processes compete with each other. Wherefore, the components and properties of interiors in neutron stars have attracted much attention (Pandharipande 1971; Glendenning 1985; Glendenning et al. 1992; Sahu et al. 1993; Kutschera & Koltraz 1993; Thorsson et al. 1994; Glendenning 1997; Alford & Reddy 2003). But actually, the equation of state for neutron star is still an indeterminacy in investigation for many years on account of kinds of reasons. Observational constraints on theoretical predictions of the equation of state of high density matter have been habitually in practice (Glendenning 1997; Glendenning & Moszkowski 1991; Zhang et al. 2007). Based on X-ray observations with the XMM Newton observatory, Cottam et al. (Cottam et al. 2002)
reported that neutron stars did not contain strange matter, but Xu (Xu 2003) addressed this conclusion was incorrect. He found that we still could not rule out strange star models for the X-ray burster EXO 0748-676 from the mass-radius relations for bare and crusted strange stars. Recently an accumulation of neutron-star cooling observations also favors the presence of exotic particles such as hyperons, quark matter in the cores of some neutron stars (Yakovlev & Pethick 2004). Lackey et al. have immediately given a particular discussion concerning the existence of hyperons by comparing with the maximum observables, i.e., stellar masses and gravitational redshifts (Lackey et al. 2006). Alford et al. and Klähn et al. have ever studied the effect of quark matter inside compact stars on the mass-radius relationship. Klähn et al. used NJL (Nambu–Jona–Lasinio) model for quark matter (Klähn et al. 2006ab). Alford et al. modelled the quark matter equation of state through a phenomenological parameterization (Alford et al. 2005), but their parameterization formalism was based on the consideration of the perturbative QCD corrections. Moreover, they mainly focused on the maximum masses of hybrid stars in accordance with the construction of a sharp transition in their work. We also estimate the circumstance with the inclusion of quark matter, but the first transition in hybrid stars is based on the Gibbs construction. We expect to uncover how the change of the region embodying mixed phase and quark matter increases the maximum masses of hybrid stars. We apply GPS (Ghosh–Patak–Sahu) model (Ghosh et al. 1995) together with an extended MIT bag model for hybrid stars. The extended MIT bag model is so-called "effective mass bag model" presented by Schertler et al. (Schertler et al. 1997).

In this model, medium effects are taken into account in the framework of the MIT bag model by introducing density-dependent effective quark masses. Such quark matter system in quasiparticle description may involve partial nonperturbative contributions since the coupling constant $g$ can be not small as shown below. According to the Tolman-Oppenheimer-Volkoff theory (Oppenheimer & Volkoff 1939), differences of equations of state would cause different mass-radius relations and in all the maximum masses. Based on mass and radius of a neutron star, the gravitational redshift can immediately be determined. Well then the observed neutron stars’ masses and gravitational redshifts would set a limit on the equation of state. Our investigations emphasize on the influence of equation of state of quark matter on the limits of stars’ mass and gravitational redshift under the consideration whether quark matter exist in compact stars or not.

The most precise observations of neutron-star masses come from radio pulsars in binaries, which are all measured with 95% confidence to be less than 1.5 $M_\odot$ (Thorsett & Chakrabarty 1999), such as the most accurately measured mass up to now but not necessarily the maximum possible mass of PSR 1913+16 with $M = 1.442 \pm 0.003 M_\odot$ (Taylor & Weisberg 1989). X-ray measurements have long suggested that accreting neutron stars are more massive, but the contamination by oscillations of the high-mass main sequence companion has been known (van Kerkwijk et al. 1995). So the record of 1.5 $M_\odot$ has remained the constraint for many years until Nice et al. obtained a neutron-star mass greater than 1.6 $M_\odot$ at the 95% confidence lever through recent radio observation of PSR J0751+1807 (Nice et al. 2003; Nice et al. 2004; Nice et al. 2005). Also Ransom et al. discovered that the relativistic periastron advance for the two eccentric systems in the globular cluster Terzan 5 indicates the existence of at least one of the pulsars that has mass $> 1.68 M_\odot$ at 95% confidence (Ransom et al. 2005).

Lackey et al. suggested that the bound on the maximum neutron-star mass is $\approx 1.68 M_\odot$ (Lackey et al. 2006). However, Özel, in an analysis of EXO 0748-
676 observational data, found that the neutron-star mass could only be low to 1.82 $M_\odot$ within $1 - \sigma$ bar (Özel 2006). Although the result has been recently disproved in an alternative analysis by Hynes et al. (Hynes et al. 2006), we still utilize the limit of mass because the equations of state of pure hadron matter have predicted such heavy stars. Another constraint is the measurement of a gravitational redshift by Cottam et al. (Cottam et al. 2002). They have analysed the absorption lines in the spectra of 28 bursts of the Low-mass X-ray binary EXO 0748-676. They discovered that several absorption lines consistent with a redshift $z = 0.35$ although with small uncertainties that no more than 5% for the respective transitions.

The organization of the rest of this paper is as follows. In section 2, we provide details of equations of state for strange stars and hybrid stars. In section 3 and 4, we estimate the constrains of observational mass and gravitational redshift on the equations of state for strange stars and hybrid stars respectively. Finally, we give the conclusions and discussions in section 5.

2 EQUATION OF STATE

2.1 Strange stars

A strange star is composed of pure strange quark matter, which is made up of up, down, strange quarks and leptons. For quark matter, it is in nature that the equation of state must be calculated by lattice quantum chromodynamics, but this couldn’t be carried through at finite density, so researchers often adopt some phenomenological models in calculation (Baym & Chin 1976; Freedman & McLerran 1978; Chakrabarty 1991; Peng et al. 2000). Here we mainly take the effective mass bag model considering medium effect into account (Schertler et al. 1997), which is based on quasiparticle approximation. We could consider the up, down, and strange quarks to be quasiparticles by utilizing Debye screen effect in plasma. Under this circumstance, a quark acquires an effective mass generated by the interaction with other quarks of the dense system. The effective masses are derived from the zero momentum limit of the dispersion relations following from the quark self energy. In the hard dense loop (HDL) approximation, the generic form of the quark self energy is

$$\Sigma = -a P_\mu \gamma^\mu - b \gamma_0 - c,$$

thereinto

$$a = \frac{1}{4p^2} [tr(P_\mu \gamma^\mu \Sigma) - p_0 tr(\gamma_0 \Sigma)],$$

$$b = \frac{1}{4p^2} [P^2 tr(\gamma_0 \Sigma) - p_0 tr(P_\mu \gamma^\mu \Sigma)],$$

$$c = -\frac{1}{4} tr \Sigma.$$  

Here $P^2 = p_0^2 - p^2$, then we can obtain the effective quark mass

$$m_i^* = \frac{m_i}{2} + \sqrt{\frac{m_i^2}{4} + \frac{g^2\mu_i^2}{6\pi^2}}.$$  

The mass formula depends on the coupling constant $g$, quark chemical potential $\mu_i$ and the current mass of quark $m_i$ where $i = u, d, s$. In HDL approach, one expects that $g$ ought to be small as effective mass is calculated perturbatively, but Schertler et al. (Schertler et al. 1997) extrapolated it to large value. We here take
The pressure and energy density for quark matter could be constructed through the account of the statistical mechanics of quasiparticles system,

$$\epsilon = \sum_i \left\{ \frac{d}{16\pi^2} [k_i k_i (2\mu_i^2 - m_i^2)] - m_i^4 \ln \left( \frac{k_i + \mu_i}{m_i} \right) + B^* (\mu_i) \right\} + \epsilon_e + B, \quad (6)$$

$$p = \sum_i \left\{ \frac{d}{48\pi^2} [k_i k_i (2\mu_i^2 - 5m_i^2) + 3m_i^4 \ln \left( \frac{k_i + \mu_i}{m_i} \right) - B^* (\mu_i)] + p_e - B, \quad (7)$$

where $d$ is the degree of degeneracy and $B^*$ is a function to maintain thermodynamic self-consistency.

$$\frac{dB^* (\mu_i)}{dm_i^*} = - \frac{d}{4\pi^2} \left[ m_i^* k_i - m_i^4 \ln \left( \frac{k_i + \mu_i}{m_i} \right) \right]. \quad (8)$$

Up to now, it is difficult to estimate bag constant $B$ and strange quark mass $m_s$ from available data. They are subject to systematic uncertainties, so we typically treat them as the free parameters ranging from $140^4$ to $200^4$ MeV$^4$ for $B$ and from 80 to 150 MeV for $m_s$ as many researchers have done.

### 2.2 Hybrid stars

A hybrid star mainly contains quark matter core, mixed quark-hadron phase and hadron matter if the surface tension at the boundary between the quark and hadron phase is low enough. To construct the equation of state for hybrid stars, we are firstly in need of the equations of state for hadron matter and quark matter. The equation of state for quark matter has been discussed in previous section. Generally speaking, we should use the Baym – Pethick – Sutherland (BPS) equation of state for subnuclear densities corresponding to the crust of the star, which is matched with the equation of state for nuclear densities at $\epsilon \approx 10^{14} \text{g/cm}^3$. The equation of state of hadron matter for nuclear densities could be established in relativistic mean field theory (Glendenning 1997) that is one of the effective field theories describing hadron matter, where nucleons interact through the nuclear force mediated by the exchange of isoscalar and isovector mesons ($\sigma, \omega, \rho$). We here consider the hadron phase including only four kinds of particles $n, p, e, \mu$. A relativistic Lagrangian reads

$$L = \sum_{B=n,p} \bar{\psi}_B (i\gamma^\mu \partial_\mu - m_B + g_{\sigma B} \sigma - g_{\omega B} \gamma_\mu \omega^\mu - \frac{1}{2} g_{\rho B} \gamma_\mu \tau \cdot \rho^\mu) \psi_B + \frac{1}{2} (\partial_\mu \sigma \partial_\mu \sigma - m_\sigma^2 \sigma^2) - U(\sigma) + \sum_{\lambda=e,\mu} \bar{\psi}_\lambda (i\gamma_\mu \partial_\mu - m_\lambda) \psi_\lambda - \frac{1}{4} \omega_{\mu\nu} \omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_{\mu\nu} \omega^{\mu\nu} - \frac{1}{4} \rho_{\mu\nu} \cdot \rho^{\mu\nu} + \frac{1}{2} m_\rho^2 \rho_{\mu\nu} \cdot \rho^{\mu\nu}. \quad (9)$$

We then solve the Euler-Lagrange equations of (9) by replacing the fields by their mean values under the assumption that the bulk matter is static and homogeneous and then calculate the kinetic Dirac equations for baryons and also the meson fields equations. By imposing $\beta$-equilibrium, local electric charge neutrality and conservation of baryon number, we obtain the equation of state for pure hadron
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\[ \epsilon = \frac{1}{3} b m_n (g_\sigma \sigma)^3 + \frac{1}{4} c (g_\sigma \sigma)^4 + \frac{1}{2} m_\omega^2 \sigma^2 + \frac{1}{2} m_\rho^2 \rho_0 + \frac{1}{2} m_\rho^2 \rho_0 \]
\[ + \sum_{B=n,p} \frac{2 J_B + 1}{2 \pi^2} \int_0^{k_B} \sqrt{k^2 + (m_B - g_\sigma B \sigma)^2} k^2 dk \]
\[ + \sum_{\lambda} \frac{1}{\pi^2} \int_0^{k_\lambda} \sqrt{k^2 + m_\lambda^2} k^2 dk, \] (10)

\[ p = -\frac{1}{3} b m_n (g_\sigma \sigma)^3 - \frac{1}{4} c (g_\sigma \sigma)^4 - \frac{1}{2} m_\omega^2 \sigma^2 + \frac{1}{2} m_\rho^2 \rho_0 + \frac{1}{2} m_\rho^2 \rho_0 \]
\[ + \frac{1}{3} \sum_{B=n,p} \frac{2 J_B + 1}{2 \pi^2} \int_0^{k_B} \frac{k^4}{\sqrt{k^2 + (m_B - g_\sigma B \sigma)^2}^2} dk \]
\[ + \frac{1}{3} \sum_{\lambda} \frac{1}{\pi^2} \int_0^{k_\lambda} \frac{k^4}{\sqrt{k^2 + m_\lambda^2}} dk. \] (11)

Actually, the Euler-Lagrange equations feature five free parameters, which under certain assumptions are fit algebraically to numbers distilled from laboratory measurements of many finite nuclei, i.e., the saturation density, binding energy per nucleon and symmetry energy coefficient at saturated nuclear matter, and the overall compressibility \( K \) and the effective mass of nucleons \( m^* \). As it is not our motive here, we numerically adopt five fiducial equations of state using Glendenning \( GL \) (Glendenning 1997) and Ghosh – Patak – Sahu \( GPS \) (Ghosh et al. 1995) parameters for demonstration, which are arranged in Table 1 and represent the equation of state from the softest to the stiffest respectively.

Under the consideration of the models of the compact stars inside which the deconfinement transition occurs at high density (Glendenning 1992; Glendenning 1997), we allow hadron phase to undergo a first order phase transition (Schertler et al. 1998; Schertler et al. 2000) to a deconfined quark matter phase above the saturation density of nucleon. This phase transition makes it possible that the occurrence of a mixed hadron-quark phase in a finite density range inside compact stars. Based on the quark and hadron matter equations of state, \( \beta \)-equilibrium, global electric charge neutrality and Gibbs condition between quark and hadron phases, we could easily get the equation of state for mixed phase, and then the equation of state for hybrid stars.

3 MAXIMUM MASS

The structure of a neutron star is determined by the local balance between the attractive gravitational force and the pressure force of the neutron star matter. For an equilibrium neutron star under the condition of overlooking the effect of rotation, the gravitational field is taken to be static and spherically symmetric. Considering the effect of general relativity, Tolman, Oppenheimer and Volkoff established a set of equations (TOV equations) (Oppenheimer & Volkoff 1939) to determine the structures of these stars:

\[ \frac{dp(r)}{dr} = -\frac{[\epsilon(r) + p(r)][m(r) + 4\pi r^3 p(r)]}{r[r - 2m(r)]}, \] (12)

\[ \frac{dm(r)}{dr} = 4\pi r^2 \epsilon(r). \] (13)
Here $G = c = 1$, $p(r)$ and $\epsilon(r)$ are the pressure and energy density of the matter at the radius $r$, and $m(r)$ is the total mass inside the star within a sphere of given radius $r$:

$$m(r) = 4\pi \int_0^r \epsilon(r') r'^2 dr'.$$

(14)

After the equation of state of the star $\epsilon(r) = \epsilon(p(r))$ is given, the TOV equations could be finally solved as an initial value problem. Stating the values of the pressure $p(r = 0) = p_c$ and mass $m(r = 0) = 0$ in the center of the star, we can integrate the TOV equations outwardly until the surface $p(r = R) = 0$ is reached, then we could give the $M - R$ relation of the star, which has a maximum mass under the prediction of the general relativity. Using this property, we can rule out those equations of state that are too soft to produce the observed masses. Actually, Ter 5 I rotates at 104 Hz (Ransom 2005) and EXO 0748-676 at 45 Hz (Villarreal & Strohmayer 2004), which may increase the TOV maximum mass less than 1%. On analysing the theoretical results with observational data, we should also take this small correction into account.

In Fig.1, we plot the $R - M$ relation for strange stars based on our fiducial effective mass bag model considering medium effect. We find that the consideration of medium effect and the increase of the current mass of $s$ quark $m_s$ could only slightly soften the equation of state, but the change of bag constant $B$ can affect the stiffness of equation of state distinctly. And only the ones with smaller bag constant are necessary for strange stars to be consistent with the higher mass limits.

We investigate the influence of the hadronic equations of state on the ones for hybrid stars in Fig.2. It displays little effect on the stiffness of the equations of state for hybrid stars and in all the maximum mass, which could also be seen below for gravitational redshift. Our choice of the intermediate one, GPS2, as our primary to estimate the equations of state of hybrid stars suffices present needs. In Fig.3, we show the $R - M$ relation for hybrid stars. The symbol crosses on each curve represent the dividing point of the hadron phase and mixed phase. Only the compact stars lie in the district between the cross and the maximum mass point could have quark matter in the interior. The coupling constant for strong action $g$ as well as the bag constant $B$ influence the stiffness of the equation of state for hybrid stars remarkably. For $g = 0.0$ condition, almost all the equations of state with quark matter are ruled out by both limits of mass, except the stiffest one with parameters $B^{1/4} = 200.0\text{Mev}$, $m_s = 150.0\text{Mev}$ which can be brought within the 95% confidence limit of $1.68\ \text{M}_\odot$ from Ter 5 I account for the rotation correction. Under $g = 3.0$, both curves are consistent with the limit from Ter 5 I but only the ones with $B^{1/4} = 200.0\text{Mev}$ could fit the 1.82 $\text{M}_\odot$. And when $g = 4.0$, all equations of state reach the larger constraint 1.82 $\text{M}_\odot$. After $g = 5.0$, quark matter disappears in the neutron stars. The equations of state of pure nucleonic matter are consistent with 1.68 $\text{M}_\odot$ and 1.82 $\text{M}_\odot$. Obviously, the hybrid stars with medium effect of quark matter are very different from the ones without medium effect. The reason for the existence of heavy hybrid star is that increasing $g$ and $B$ soften the EOS of quark matter, which heightens the transition density and cause difficulty to occur from hadrons to quark matter and in all hardens the EOS of hybrid star. This effect brings about a hybrid star dominated by hadronic matter, i.e., the extent of quark matter reduces but the hadron matter region increases and this in fact yields "hybrid" stars that are actually hadronic stars with a tiny core of mixed quark-hadron matter inside and the most of the mass and radius contributions come from the hadron mat-
ter, so the Mass-radius relation of hybrid star has the tendency towards the pure neutron star and the heavier stars appear.

4 GRAVITATIONAL REDSHIFT

As is known by deduction of general relativity, when photons emit from radiant point in a gravitational field, the spectrum line would shift to the red part of spectrum observed from the place apart from the field. This phenomena is called gravitational redshift. Generally speaking, the quantity of gravitational redshift is small, expect around the black holes or neutron stars which have a strong gravitational field. For a nonrotating star, the redshift $z$ obeys the relation

$$z = (1 - \frac{2M}{R})^{-1/2} - 1,$$

which is evidently relevant to the value of $M/R$ and could permit a determination of the mass-to-radius ratio as its potential usefulness in measurements for compact stars. Attentively, we have already known from the curve of $M - R$ relation that $R$ decreases with $M$ until $M$ approaches its maximum for a stable star. The redshift spontaneously has a maximum at the point of maximum-mass star, which could be also used to rule out the equations of state that can’t produce a redshift in observation. Cottam et al. (Cottam et al. [2002]) have analysed the absorption lines in the spectra of 28 bursts of the Low-mass X-ray binary EXO 0748-676. They identified the most significant features with Fe XXVI and XXV $n = 2 - 3$ and O VIII $n = 1 - 2$ transitions and discovered all transitions with a redshift $z = 0.35$ although with small uncertainties for the respective transitions. Recent observation suggests that the neutron star rotates at 45 Hz (Villarreal & Strohmayer [2004]), but we still consider nonrotating approximation as the rotation correction to the redshift should be small.

We plot the redshift as a function of mass for strange stars based on our fiducial effective mass bag model considering medium effect in Fig.4. All the equations of state are consistent with $z = 0.35$. Together with the maximum mass constraint discussed in the section 3, we conclude that the observation mass constraint acts on the equations of state for quark matter strongly, as well as the free parameters especially the bag constant $\bar{B}$ in strange stars.

Analogically, we investigate the influence of the hadronic equations of state under the consideration of relativistic mean-field theory on $\text{Redshift}(M)$ of hybrid stars in Fig.5 as done in Fig.2. The maximum redshifts are not sensitive to the equations of state for hadrons but to the ones of quark matter at several times nuclear density, which could also be seen in Fig.6. Contrast to the maximum masses limits, the ones with $B^{1/4} = 170.0\text{Mev}$ under $g = 0.0$ are both consistent with the redshift constraint 0.35, and the circs for $B^{1/4} = 200.0\text{Mev}$ are opposite. This means that both equations of state without medium effect must be excluded by the observational constraints. For $g = 3.0$ and $g = 4.0$, all equations of state with quark matter are consistent with $z = 0.35$. The equations of state under the case $g = 5.0$ are also compatible with the constraint but quark matter is absent.

5 CONCLUSION

We have compared equations of state for quark matter in quasiparticle description in strange stars and hybrid stars with astronomical observations of mass and gravitational redshift. We study effect of the coupling strength among quarks on strange stars and hybrid stars. In strange stars, the effect of the coupling constant is small to reach the observational limits. In hybrid stars, however, the coupling
constant play an important role in maximum masses and gravitational redshifts of the stars. We think that hybrid star is a more realistic model, where intermediate dense strange quark matter is possible. The hybrid stars have masses much lower than the observed masses when quark matter exists as a free fermion gas, but can produce the observed mass and redshift when medium effect of strange quark matter is taken into account. The studies in section 3 and 4 have shown that intermediate coupling constant may be the best choice for making the equations of state for hybrid stars consistent with both the observation mass and redshift constraints better for a wide range of parameter $B$.

In quality, we can obtain the similar maximum masses given by Alford et al. (Alford et al. 2005) that the presence of quark matter in the neutron stars is constrained but not ruled out by the observational mass and gravitational redshift. However, there are quite evident differences between the investigation of Alford et al. and ours. Firstly, our model contains large coupling constant $g$ (or $\alpha_c = g^2/4\pi^2 > 1$) which is slightly different from parameterized EOS based on perturbative QCD theory. Secondly, the heavier hybrid star is dominated by quark matter for the case of the sharp transition while in our configuration by hadronic matter. The reason is that the softening of EOS of quark matter leads to the existence of the almost pure hadron star in our model. In sharp transition, Alford et al. owe it to the hardening of the quark matter EOS by increasing $c$ and in all the existence of a much more larger quark matter core. Our work also indicates that there is a critical value of $g \sim 5.0$ over which quark matter cannot exists inside the stable neutron stars.

It is well-known that cooling measurements is an additional constraints on equation of state of compact stars. Current measured temperatures of compact objects are compatible with strange stars and hybrid stars (Yu & Zheng 2006, Kang & Zheng 2006). Existence of hyperons and quark matter in compact objects indicates that these such equations of state tend to result in excessively fast cooling due to the onset of direct Urca processes, and so is the stiff nucleonic equation of state in heavier stars (Page et al. 2006). Thus the normal neutron stars or hyperon stars may be much cooler to be ruled out by X-ray data. However, the hybrid stars do not have this problem because a deconfinement heating mechanism is triggered due to the spin-down of the stars. We discovered that the deconfinement latent heat can effectively cancel the enhanced neutrino emission (Kang & Zheng 2006).

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Table 1 Parameters for five fiducial hadronic equations of state in relativistic mean-field theory. \( \rho_0 \) is the saturation density, \( B/A \) is the binding energy, the incompressibility is denoted by \( K \), the effective mass by \( m^*/m_N \) and the symmetry energy by \( a_{\text{sym}} \).

| Name | \( \rho_0 (\text{fm}^{-3}) \) | \( B/A \text{(Mev)} \) | \( a_{\text{sym}} \text{(Mev)} \) | \( K \text{(Mev)} \) | \( m^*/m_N \) | EOS            |
|------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| GL1  | 0.153               | -16.3               | 32.5                | 240                 | 0.78                | softest             |
| GPS1 | 0.150               | -16.0               | 32.5                | 250                 | 0.83                | soft               |
| GPS2 | 0.150               | -16.0               | 32.5                | 300                 | 0.83                | intermediate        |
| GPS3 | 0.150               | -16.0               | 32.5                | 350                 | 0.83                | stiff              |
| GL2  | 0.153               | -16.3               | 32.5                | 300                 | 0.7                 | stiffest            |


Fig. 1 Oppenheimer-Volkoff radius-mass curves for strange stars using effective mass bag model considering medium effect (bottom) and not (top). These two vertical lines represent the observational 95% confidence limit 1.68 $M_\odot$ from Ter 5 I and 1.82 $M_\odot$ within $1 - \sigma$ bar from EXO 0748-676. $B$, $g$ and $m_s$ are bag constant, coupling constant and the current mass of s quark respectively. These seven sets of four curves in each panel represent the results assuming seven different values about $B^{1/4}$ ranging from 200 Mev (ie. the left set) to 140 Mev (ie. the right set) with equal intervals of 10 Mev.
Fig. 2 Oppenheimer-Volkoff radius-mass curves for hybrid stars with the same equation of state for quark matter and different equation of state for hadrons (GL1, GPS1, GPS2, GPS3, GL2). These two vertical lines represent the observational 95% confidence limit 1.68 M⊙ from Ter 5 I and 1.82 M⊙ within 1 − σ bar from EXO 0748-676. For quark matter, we choose the parameters $B^{1/4} = 170.0$ Mev, $g = 0.0$ and $m_s = 150.0$ Mev in calculation.
Fig. 3  Oppenheimer-Volkoff radius-mass curves for hybrid stars with same equation of state for hadrons (GPS2), and the symbol cross on each curve represents the dividing point of the hadron phase and the mixed phase. These two vertical lines represent the observational 95% confidence limit $1.68 \, M_\odot$ from Ter 5 I and $1.82 \, M_\odot$ within $1 - \sigma$ bar from EXO 0748-676. These two sets of three curves represent the results of two different values about $B_{1/4}$ which ranges from 170 Mev (ie. the left set) to 200 Mev (ie. the right set) in the upper two panels, from 160 Mev (ie. the left set) to 200 Mev (ie. the right set) in the third panel, and from 140 Mev (ie. the left set) to 200 Mev (ie. the right set) in the fourth panel.
Fig. 4 Gravitational redshift vs mass for strange stars using effective mass bag model considering medium effect (bottom) or not (top). The horizontal line is $z = 0.35$ measured for EXO0748-676. These seven sets of four curves in each panel represent the results assuming seven different values about $B^{1/4}$ ranging from 200 Mev (ie. the left set) to 140 Mev (ie. the right set) with equal intervals of 10 Mev.
Fig. 5 Gravitational redshift vs mass for hybrid stars with the same equation of state for quark matter and different equation of state for hadrons (GL1, GPS1, GPS2, GPS3, GL2). The horizontal line is $z = 0.35$ measured for EXO0748-676. For quark matter, we choose the parameters $B^{1/4} = 170.0\text{Mev}$, $g = 0.0$ and $m_s = 150.0\text{Mev}$ in calculation.
Fig. 6 Gravitational redshift vs mass for hybrid stars with same equation of state for hadrons (GPS2), and the symbol cross on each curve represents the dividing point of the hadron phase and the mixed phase. The horizontal line is $z = 0.35$ measured for EXO0748-676. These two sets of three curves represent the results of two different values about $B^{1/4}$ which ranges from 170 Mev (ie. the left set) to 200 Mev (ie. the right set) in the upper two panels, from 160 Mev (ie. the left set) to 200 Mev (ie. the right set) in the third panel, and from 140 Mev (ie. the left set) to 200 Mev (ie. the right set) in the fourth panel.