Searching For Strange Quark Planets

Xu Wang\textsuperscript{1,\ast}, Yong-Feng Huang\textsuperscript{1,2,\ast} and Bing Li\textsuperscript{3,4}

\textsuperscript{1}School of Astronomy and Space Science, Nanjing University, Nanjing 210023, People’s Republic of China
\textsuperscript{2}Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, People’s Republic of China
\textsuperscript{3}Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
\textsuperscript{4}Particle Astrophysics Division, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People’s Republic of China

\textsuperscript{\ast}E-mail: wx\_tba@163.com; hyf@nju.edu.cn

Strange quark matter (SQM) may be the true ground state of matter. According to this SQM hypothesis, the observed neutron stars actually should all be strange quark stars. But distinguishing between neutron stars and strange quark stars by means of observations is extremely difficult. It is interesting to note that under the SQM hypothesis, less massive objects such as strange quark planets and strange dwarfs can also stably exist. The extremely high density and small radius of strange quark planets give us some new perspectives to identify SQM objects and to test the SQM hypothesis. First, the tidal disruption radius of strange quark planets is much smaller than normal planets, so, very close-in exoplanets can be safely identified as candidates of SQM objects. Second, gravitational waves (GW) from mergers of strange quark star-strange quark planet systems are strong enough to be detected by ground-based GW detectors. As a result, GW observation will be a powerful tool to probe SQM stars. At the same time, the tidal deformability of SQM planets can be measured to further strengthen the result.

\textbf{Keywords:} Strange quark stars, Exoplanets, Gravitational waves, Neutron stars

\section{1. Introduction}

The central engine of gamma-ray bursts may be compact objects such as neutron stars. However, our knowledge about matter under extreme densities is still quite poor so that the internal composition and structure of neutron stars are largely uncertain to us\textsuperscript{11}. It has been argued that the energy per baryon of strange quark matter (SQM), which is composed of three favors of quarks (up, down and strange quarks), could be less than normal hadronic matter. As a result, SQM may be the true ground state of matter\textsuperscript{10,11}. If this hypothesis is true, then it is even possible that all the so called “neutron stars” observed in the Universe should actually be strange quark stars\textsuperscript{10,11}.

However, it is difficult to distinguish between strange quark stars and neutron stars through current astronomical observations. For a long time, people have tried to find the difference between neutron stars and strange quark stars in terms of mass-radius relationship, cooling rate, the minimum spin period and gravitational wave (GW) features. But for a typical 1.4 M\textsubscript{\odot} compact object, the radius difference between a neutron star and a quark star is too small to be detected through current
observational technology. Recently, Geng et al pointed out that fast radio bursts may originate from the collapses of the crust of strange quark stars. It provides an novel visual angle on these interesting objects.

It is interesting to note that, under the SQM hypothesis, quark matter is bounded by strong interaction but not gravity. So, SQM can even exist stably in the form of small chunks in the universe. It implies that planets composed of strange quark matter can also exist stably. Strange quark planets are very different from normal planets. They have a much higher mean density and a much smaller radius, which provide us with some effective new methods to test the SQM hypothesis. In our previous studies, we have suggested some new methods to identify strange quark planets. In this article, we will summarize the results.

2. Searching for strange quark planets among close-in exoplanets

Planets cannot be too close to their host stars, otherwise they will be tidally broken up by the strong tidal force of their hosts. We can use the tidal disruption radius $r_{td}$ to describe the shortest possible separation between a planet and its host, which can be analytically expressed as:

$$r_{td} \approx \left( \frac{6M}{\pi \bar{\rho}} \right)^{\frac{1}{3}}, \quad (1)$$

where $M$ is the mass of the host star and $\bar{\rho}$ is the mean density of the planet. For the convenience of calculation, this equation can be further written as,

$$r_{td} \approx 2.37 \times 10^6 \left( \frac{M}{1.4M_\odot} \right)^{\frac{1}{3}} \times \left( \frac{\bar{\rho}}{4 \times 10^{14} \text{g cm}^{-3}} \right)^{-\frac{1}{3}} \text{cm}. \quad (2)$$

Suppose a planet orbits around a host star which has a typical mass of 1.4 $M_\odot$. For a strange quark planet, its mean density can be as high as $4 \times 10^{14} \text{g cm}^{-3}$. With such a high density, the $r_{td}$ of the strange quark planet will be less than $2.37 \times 10^6$ cm, which is only about twice the radius of a pulsar. But for normal matter planets, the density is on the order of $\sim 8 \text{ g cm}^{-3}$, and the corresponding $r_{td}$ is generally larger than $8.7 \times 10^{10}$ cm. Even if we take the mean density as $30 \text{ g cm}^{-3}$, which is already a very high value for normal matter, the derived $r_{td}$ will still be larger than $5.6 \times 10^{10}$ cm. From these simple calculations, we argued that if the orbital radius of a planet is found to be less than $5.6 \times 10^{10}$ cm, then the planet should be a strange quark planet.

An extremely close-in strange quark planet cannot be observed directly by imaging method. On the contrary, it can be relatively easily detected via pulsar timing observations. According to Kepler’s law, the relationship between the orbital radius and the period can be expressed as

$$\frac{a^3}{P_{\text{orb}}^2} \approx \frac{GM}{4\pi^2}, \quad (3)$$
where $G$ is the gravity constant, $a$ is the orbital radius and $P_{\text{orb}}$ is the planet’s orbital period. For planets with $a$ smaller than $\sim 5.6 \times 10^{10}$ cm, the orbital period will be less than $\sim 6100$ s. Therefore, it is argued a planet with the orbital period less than $6100$ s should be a strange quark planet.\(^{10,11}\)

Using the above criterion, Kuerban et al. have tried to search for strange quark planets among exoplanets, especially among pulsar planets.\(^{15}\) According to their results, the short period pulsar planets of PSR J0636 b, PSR J1807-2459A b and PSR 1719-14 b are good candidates of strange quark planets.

### 3. Searching for strange quark planets through GW observations

Since 2015, gravitational wave observations have opened a new window for astronomy\(^{17}\) and are also expected to be a new tool for searching for quark stars.\(^{18}\) Note that it is still quite difficult to distinguish between binary neutron star mergers and binary quark star mergers by gravitational wave observations, because these two kinds of compact stars have marginal difference in radius at the typical mass of 1.4 $M_\odot$.\(^{19,20}\) However, gravitational waves may bring new opportunities in searching for strange quark planets.

A normal matter planet can not be too close to its host, otherwise it will be tidally disrupted. Consequently, the gravitational wave emissions from normal planetary systems are usually too weak to be detected. But due to the extremely high density and the very close-in orbit of strange quark planets, a strange star-strange planet system can produce very strong gravitational wave emissions, especially at the final stage of the merging process. If such a merger event occurs in the local universe, it would be detectable for the gravitational wave detectors such as Advanced LIGO and the Einstein Telescope.\(^{12}\)

GW observations can also help diagnose the internal composition and internal structure of compact stars by means of tidal deformability measurements. The first tidal deformability measurement has been obtained for the binary neutron star merger event of GW170817, which gives a new constraint on the equation of state of dense matter.\(^{21,22}\)

Tidal deformability is a quantity that describes the deformation of a star in a tidal field, which is defined as

$$\lambda = -\frac{Q_{ij}}{E_{ij}},$$

where $Q_{ij}$ is the induced quadrupole moment of the star and $E_{ij}$ is the tidal field that it resides in (i.e., the gravity field produced by its companion). For convenience, this quality is often written in a dimensionless form, i.e.,

$$\Lambda = \frac{\lambda c^{10}}{G^4 m^5}.$$  \hspace{1cm} (5)

Here, $c$ is the speed of light in vacuum and $m$ is the mass of the star.
Generally speaking, a larger tidal deformability means that the star will be relatively easier to be deformed in a tidal field\textsuperscript{22}. So, tidal deformability will affect the evolution of the gravitational wave phase, which could be perceived in GW observations\textsuperscript{13}. Comparing the observed tidal deformability with that calculated by solving the Tolman-Oppenheimer-Volkoff equation adopting a particular equation of state (EoS), we can get useful information on the internal structure of compact stars\textsuperscript{23,24}.

![Diagram showing tidal deformability and dimensionless tidal deformability versus mass for strange quark stars and strange quark planets. Different line styles represent different bag constant, which is marked in the figure in units of MeV/fm\textsuperscript{3}.](image)

Following the method of Hinderer et al.\textsuperscript{23,24}, we have calculated the tidal de-
formability of strange quark stars, paying special attention on strange dwarfs and strange planets. We engage the bag model for strange quark matter\textsuperscript{[2]}. Our results are shown in Figure\textsuperscript{[1]} We see that as the mass decreases, the value of the deformability also decreases, while the value of the dimensionless tidal deformability keeps increasing. For a planet with a mass of $10^{-3} M_{\text{Jup}}$, its tidal deformability is up to $\sim 10^{27}$ g cm$^2$ s$^2$ and its dimensionless tidal deformability is up to $\sim 10^{23}$, which are much higher than those of normal matter planets. Therefore, the tidal deformability is a useful parameter for identifying strange quark planets\textsuperscript{[13]}.

4. Summary

Discriminating between neutron stars and strange quark stars is a challenging task. In this article, we try to solve the problem from a novel point of view. We mainly concentrate on strange quark planets. It is suggested that there are basically two methods to search for strange quark planets. First, we can try to find close-in pulsar planets with the orbital period less than 6100 s. Encouragingly, at least three possible strange quark planet candidates have been found. Second, we can identify strange quark planets through gravitational wave observations. It is found that the mergers of strange star-strange planet systems can produce strong gravitational wave bursts, which can potentially be detected by the advanced LIGO and the future Einstein Telescope. The tidal deformability of strange quark dwarfs and strange quark planets is specially calculated. In short, we stress that strange quark planets could be a powerful tool for clarifying the nature of the so called “neutron stars”.

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