Searching for Strange Quark Matter Objects in Exoplanets

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Abstract

The true ground state of hadronic matter may be strange quark matter (SQM). Consequently, observed pulsars may actually be strange quark stars, but not neutron stars. However, proving or disproving the SQM hypothesis still remains a difficult problem to solve due to the similarity between the macroscopic characteristics of strange quark stars and neutron stars. Here, we propose a hopeful method to probe the existence of SQM. In the framework of the SQM hypothesis, strange quark dwarfs and even strange quark planets can also stably exist. Noting that SQM planets will not be tidally disrupted even when they get very close to their host stars due to their extreme compactness, we argue that we could identify SQM planets by searching for very close-in planets among extrasolar planetary systems. Especially, we should keep our eyes on possible pulsar planets with orbital radius less than \(5.6 \times 10^{10}\) cm and period less than \(6100\) s. A thorough search in the currently detected \(2950\) exoplanets around normal main-sequence stars has failed to identify any stable close-in objects that meet the SQM criteria, i.e., lying in the tidal disruption region for normal matter planets. However, the pulsar planet PSR J1719-1438B, with an orbital radius of \(6 \times 10^{10}\) cm and orbital period of \(7837\) s, is, encouragingly, found to be a good candidate.

Key words: dense matter – planetary systems – planet–star interactions – pulsars: general – stars: neutron

1. Introduction

Normal matter is constituted of electrons and nucleons. While there is still no evidence showing that an electron can be further divided, each nucleon is found to be composed of three up and down quarks. Pulsars are generally believed to be neutron stars, which are mainly made up of neutrons that agglomerate together to form a highly condensed state. With a typical mass of \(1.4 M_\odot\) and a radius of only \(10\) km, the density of neutron stars can reach several times of nuclear saturation density at the center. However, the physics of matter at these extremely high densities is still quite unclear to us (Weber 2005). For example, hyperons, baryon resonances (\(\Sigma, \Lambda, \Xi, \Delta\)), and even boson condensates (\(\pi, K\)) may appear; quark (\(u, d\)) deconfinement may also happen. In particular, it has long been suggested that even more exotic states such as strange quark matter (SQM) may exist in the interior (Itoh 1970; Bodmer 1971; Farhi & Jaffe 1984; Witten 1984). SQM is constituted of almost equal numbers of \(u, d\), and \(s\) quarks, with the \(s\) quark number slightly smaller due to its relatively higher static mass. It has been conjectured that SQM may be the true ground state of hadronic matter (Itoh 1970; Bodmer 1971; Terazawa 1979), because its energy per baryon could be less than that of the most stable atomic nucleus, such as \(^{56}\)Fe and \(^{62}\)Ni.

The existence of strange quark stars (shortened as "strange stars") was consequently predicted based on the SQM hypothesis (also known as the Bodmer–Witten hypothesis; Farhi & Jaffe 1984; Witten 1984). Strange stars could simply be bare SQM objects or bulk SQM cores enveloped by thin nuclear crusts (Glendenning et al. 1995). The possible existence of nuclear crusts makes strange stars very much similar to normal neutron stars for a distant observer (Alcock et al. 1986), which means it is very difficult for us to distinguish these two kinds of intrinsically distinct stars. An interesting suggestion is that strange stars can spin at extremely short periods (less than \(1\) ms; Friedman & Olinto 1989; Friedman et al. 1989; Glendenning 1989; Kristian et al. 1989; Madsen 1998; Bhattacharyya et al. 2016) due to the large shear and bulk viscosity of SQM (Wang & Lu 1985; Sawyer 1989), whereas the minimum spin period \(P_{\text{spin}}\) of normal neutron stars can hardly reach the submillisecond range (Frieman & Olinto 1989; Glendenning 1989). It is thus suggested that \(P_{\text{spin}} < 1\) ms can be used as a criterion to identify a strange star (Kristian et al. 1989). However, not all strange stars should necessarily spin at such an extreme speed. Furthermore, the lifetime for a strange star to maintain a submillisecond spin period should be very short, even if it has an initial period of \(P_{\text{spin}} < 1\) ms at birth, due to very strong electromagnetic emission of the fast spinning dipolar magnetic field. On the technological aspect, it is also difficult to detect submillisecond pulsars observationally. In fact, according to the ATNF pulsar catalog (website: http://www.atnf.csiro.au/people/pulsar/psrcat), the record for the smallest spin period of pulsars is still \(1.40\) ms, and only about 80 pulsars have periods less than 3 ms among all of the \(2560\) pulsars observed so far. All of these factors make this method impractical at the moment.

It has also been noted that the mass–radius relations are different for these two kinds of stars. According to the simplest MIT Bag model (Farhi & Jaffe 1984; Krivovuchenko & Martem’yanov 1991), it is \(M \propto R^3\) for strange stars, but it is \(M \propto R^{-3}\) for neutron stars (Baym et al. 1971; Glendenning et al. 1995; de Avellar & Horvath 2010; Drago et al. 2014). Unfortunately, this method is severely limited by the fact that the masses and radii of these compact stars cannot be measured accurately enough thus far. The fact that strange stars and neutron stars have similar radii at the typical pulsar mass of \(1.4 M_\odot\) (Lattimer & Prakash 2007; Özel & Freire 2016) adds additional difficulties to the application (Panei et al. 2000). Several other methods have also been suggested, based on the different cooling
behaviors (Pizzochero 1991; Page & Applegate 1992; Lattimer et al. 1994) or the gravitational wave emissions (Jaranowski et al. 1998; Madsen 1998; Lindblom & Mendell 2000; Andersson et al. 2002; Jones & Andersson 2002; Bauswein et al. 2010; Morais & Miranda 2014; Geng et al. 2015; Mannarelli et al. 2015). But either because the difference between strange stars and neutron stars is subtle and inconclusive, or because the practice is extremely difficult currently, we still do not have a satisfactory method to discriminate them after more than 40 years of extensive investigations (Cheng et al. 1998).

It is interesting to note that small chunks of SQM with baryon number lower than 10^{17} can stably exist according to the SQM hypothesis. Consequently, there is effectively no limitation on the minimum mass of strange stars. It means the SQM version of white dwarfs, i.e., strange dwarfs, can exist, and even strange planets may be present in the universe (Glendenning et al. 1995). Noting that strange planets can spiral very close to their host strange stars without being tidally disrupted owing to their extreme compactness, Geng et al. (2015) suggested that these merger systems would serve as new sources of gravitational wave bursts and could be used as an effective probe for SQM. This is a very hopeful new method. The only concern is that it would take an extremely long time for a strange planet to have a chance to merge with its host. According to Geng et al.’s estimation, the event rate detected by even the next generation gravitational wave experiment such as the Einstein Telescope would not exceed a few per year (Geng et al. 2015). Thus, this goal is still far from attainable in the near future.

In this study, we suggest that we could probe the existence of SQM by searching for close-in planets among extrasolar planetary systems. This method can significantly increase the opportunity for success if the SQM hypothesis is correct.

2. Extremely Small Tidal Disruption Radius

Strange planets are SQM objects of planetary masses. They can be used to test the SQM hypothesis. The basic idea relies on the gigantic difference between the tidal disruption radius for an SQM planet and that for a normal matter one.

When a planet orbits around its host star, a different gravitational force (from the host star) will be exerted on different parts of the planet due to its slight difference in distance with respect to the host. This is the so-called tidal effect. The tidal force tends to tear the planet apart, but it can be resisted by the self-gravity of the planet when the two objects are still far away. When the two objects approach each other, the tidal effect will become stronger (Gu et al. 2003). There exists a critical distance, i.e., the so-called tidal disruption radius (r_{td}), at which the tidal force is exactly balanced by the self-gravity of the planet (Hills 1975). If the distance is smaller than the tidal disruption radius (r_{td}), the tidal force will dominate and the planet will be completely broken up. An analytical expression for r_{td} has been derived as

\[ r_{td} \approx (6M/\pi\rho)^{1/3}, \]

where M is the mass of the central host star and \( \rho \) is the density of the planet (Hills 1975).

SQM planets are extremely compact and their densities are typically \( \sim 4 \times 10^{14} \text{ g cm}^{-3} \). As a result, the tidal disruption radius for strange planets can be scaled as

\[
 r_{td}(\text{SQM}) \approx 1.5 \times 10^6 \left(\frac{M}{1.4 M_\odot}\right)^{1/3} \times \left(\frac{\rho}{4 \times 10^{14} \text{ g cm}^{-3}}\right)^{-1/3} \text{ cm}. \tag{1}
\]

We see that the tidal disruption radius for strange planets is as small as \( r_{td}(\text{SQM}) \sim 1.5 \times 10^6 \text{ cm} \). Thus, a strange planet will retain its integrity even when it is very close to the surface of its central host strange star.

On the contrary, the tidal disruption radius for a normal matter planet is usually much larger. For example, for typical planets with a density of 8 g cm^{-3}, the tidal disruption radius is \( \sim 8.7 \times 10^{10} \text{ cm} \). This means that, typically, a normal matter planet will be disrupted at a distance of \( \sim 10^{11} \text{ cm} \), and we will in no way be able to see a normal planet orbiting around its host at a distance much less than this value. Even when we consider a planet density as high as 30 g cm^{-3}, the tidal disruption radius will still be as large as \( \sim 5.6 \times 10^{10} \text{ cm} \).

The analyses above remind us that we could test the SQM hypothesis through exoplanet observations: if we detected a close-in exoplanet that lies in the tidal disruption region for normal matter (i.e., with the orbital radius significantly less than \( \sim 5.6 \times 10^{10} \text{ cm} \)), it must be a strange planet.

Note that when a solid asteroid (of mass \( m \), radius \( r \), and density \( \rho \)) becomes elongated in the radial direction in the centripetal gravitational field of its host (mass \( M \)), the elongation stress inside the object can also help to resist the tidal force. It will lead to a reduced tidal disruption radius. To consider this effect, we can approximate the elongated asteroid by a right circular cylinder of length 2\( r \). The elongation stress will be maximal at the asteroid center, which is (Colgate & Petschek 1981)

\[
s_c = \int_0^r 2GM d\ell = \frac{GMpr^2}{d^3}, \tag{2}
\]

where \( d \) is the distance between the asteroid and the host star. Assuming that the strength of the material is \( s \) and let \( s_c \) equal \( s \), we can derive the tidal disruption radius as (Colgate & Petschek 1981)

\[
r_{td} = (GMpr^2/s)^{1/3} \approx 2.4 \times 10^9 m_{18}^{2/9} s_{10}^{-1/3} \left(\frac{\rho}{8 \text{ g cm}^{-3}}\right)^{1/9} \times \left(\frac{M}{1.4 M_\odot}\right)^{1/3} \text{ cm}, \tag{3}
\]

where \( m_{18} = m/10^{18} \text{ g} \) and \( s_{10} = s/10^{10} \text{ dyn/cm}^2 \). This equation is applicable if the elongation stress dominates over the self-gravity. However, for an Fe–Ni planet of the Earth mass of \( M_\oplus = 6.0 \times 10^{27} \text{ g} \), density \( \rho = 8 \text{ g cm}^{-3} \), radius \( r = 5.6 \times 10^8 \text{ cm} \), and strength \( s = 10^{10} \text{ dyn cm}^{-2} \), we find \( r_{td} = 3.6 \times 10^{11} \text{ cm} \) for \( M = 1.4 M_\odot \) from the above equation. This is significantly larger than the value derived from Equation (1). If the density of the planet is higher (which is of more interest in our study), the tidal disruption radius will be
even larger. Thus, for relatively larger planets studied here, this effect is not significant and can be safely omitted.

3. Examining the Observed Exoplanets

Exoplanets can be detected in various ways (Perryman 2000). Currently, the most productive method is through transit photometry, i.e., monitoring the periodic brightness variation of the host star induced by the transit of a planet across the stellar disk. In this aspect, the Kepler mission is undoubtedly the most successful project (Borucki 2016). Kepler is a space-based optical telescope of 0.95 m aperture. It was launched in 2009 by NASA to monitor ~170,000 stars over a period of four years. With a 105 square degree field-of-view and ~10 ppm photometry accuracy, it successfully detected over 4600 planetary candidates and confirmed over 1000 exoplanets. An important advantage of the transit photometry method is that it is possible to measure the size of the planet, so that its density can be derived (Borucki 2016). In some special cases, even the atmosphere of the planet can be probed (Armstrong et al. 2016). Another widely used method is through radial velocity measurement, which inspects the regular radial velocity variations of the host star caused by the orbital movement of the planet. Long-term accuracies of the host’s radial motions of several meters per second are needed, which can effectively yield all orbital elements of the planets except the orbital inclination. Third, for pulsar planets, timing observation is an effective method, as the orbital motion of planets will affect the arrival times of the pulsar’s radio pulses. In fact, the first extrasolar planet was detected orbiting around PSR B1257+12 solely by this method (Wolszczan & Frail 1992). Finally, several other less commonly used methods, such as astrometry, gravitational microlensing, and direct imaging, have also been successfully applied and led to the detection of a small portion of the currently known exoplanets.

Due to continuous improvements in the observational techniques above, the number of observed exoplanets has expanded quickly in recent years (Han et al. 2014; Coughlin et al. 2016). Several catalogs are available for exoplanets, such as the Exoplanet Orbit Database (shortened as EOD hereafter) at exoplanet.eu, the Extrasolar Planets Encyclopaedia at exoplanet.eu, the NASA Exoplanet Archive at exoplanetarchive.ipac.caltech.edu, and the Kepler exoplanet catalog at archive.stsci.edu/kepler. In this study, we use the EOD database to carry out the statistics. As of 2017 May 27, there are 5288 planets in the catalog, of which 2950 are confirmed planets and 2338 are candidates. Among the confirmed planets, 322 samples are tabulated with inferred density, and an additional 2108 samples are tabulated with both mass and radius values so that their densities can be calculated. The planet masses are available for 2937 planets, and the orbital radii are given for 2925 samples. With so many exoplanets in hand, we can try to search for possible SQM objects in them.

Because planet density is a key factor in determining the tidal disruption radius, in Figure 1 we plot the density distribution for all of the confirmed exoplanets with densities available (2430 objects in total). The densities of most exoplanets (about 99% of all the samples) are less than 10 g cm$^{-3}$. Only four exoplanets are listed as denser than 30 g cm$^{-3}$. Note that these high-density planets (with $\rho > 30$ g cm$^{-3}$) generally have large error bars; thus, their density measurements are highly uncertain. Figure 1 indicates that for the density of normal hadronic planets, we can take 30 g cm$^{-3}$ as a reasonable upper limit.

According to Equation (1), the tidal disruption radius is $r_{\text{td}} \approx 5.6 \times 10^{10}$ cm when the planet density is 30 g cm$^{-3}$, and the host star mass is $1.4 M_{\odot}$. So, a direct strategy is to see whether there are any close-in exoplanets with an orbital radius significantly less than the critical radius of $5.6 \times 10^{10}$ cm. In Figure 2, we plot the distribution of orbital radius ($a$) for all of the confirmed exoplanets (2925 objects in total). Typically, the orbital radii are between 0.03 and 10 au. For exoplanets around normal main-sequence stars, only three objects have radii less than 0.01 au. The smallest radius is 0.006 au ($9 \times 10^{10}$ cm), but even this value is still well above the critical tidal disruption radius of $5.6 \times 10^{10}$ cm for a very dense object of $\rho \sim 30$ g cm$^{-3}$. Thus, no clear clues pointing to the existence of strange planets around normal main-sequence stars are revealed from this plot.

Because the tidal disruption radius depends on both the planet density and the host star mass, it is more reasonable to...
evaluate the closeness of planets by comparing their orbital radii with the corresponding tidal disruption radii. We thus define the closeness of planets as $a/r_{td}$. For the planets with densities available (2430 objects, around main-sequence stars), we have calculated their tidal disruption radii ($r_{td}$) and the corresponding closeness parameter. Figure 3(a) illustrates the mass distribution versus the closeness of these planets. It can be clearly seen that all of the planets lie outside of the tidal disruption region, which proves $a > r_{td}$ as a definite limitation for the survival of planets. For the remaining 520 exoplanets without a density measurement (as listed in the EOD database), we have assumed a typical value of $8 \text{ g cm}^{-3}$ for them and plotted their distributions in Figure 3(b). Again, we see that no planets lie within the tidal disruption region.

From Figure 3, it can be seen that no clues pointing toward the existence of any SQM objects can be found in the EOD database. This is not an unexpected result. SQM planets, if they truly exist, are not likely to be found orbiting around normal main-sequence stars, but should be around compact stars (especially, strange stars). Thus, we should pay special attention to exoplanets around pulsars. Note that for pulsar planets, the transit photometry method is not effective, and we will primarily rely on the pulsar timing method to detect them. In this case, the densities of the planets are usually unavailable. In fact, at least five planets have been detected orbiting around three pulsars (Lorimer 2008; Martin et al. 2016), i.e., PSR B1257+12 (Wolszczan & Frail 1992), PSR J1719-1438 (Bailes et al. 2011), and PSR B1620-26 (Backer et al. 1993; Sigurdsson et al. 2003). PSR B1257+12 has three planets, and each of the other two planets has one planetary companion. All of these planets are detected through the pulsar timing method; thus, no radius measurements are directly available for them. In Figure 3(b), we have also plotted the five pulsar planets, represented by red star symbols. Again, we assumed a typical density of $8 \text{ g cm}^{-3}$ in the plot. While four pulsar planets are safely beyond the tidal disruption region, we do notice that one planet lies in the disruption region (with $a/r_{td} = 0.69$). It is associated with PSR J1719-1438, a 5.7 ms pulsar, with an orbital radius of $\sim 6.0 \times 10^{10}$ cm and orbital period of $\sim 2.2$ hr. Interestingly, this problem has already been noticed by Bailes et al. who argued that this companion must be denser than $23 \text{ g cm}^{-3}$ to survive the strong tidal force of its host (Bailes et al. 2011). They even went further to suggest that the planetary companion may actually be a carbon white dwarf. However, with a mass comparable to that of the Jupiter, it seems far too rare for a white dwarf to have such an ultralow mass. A more reasonable suggestion has been made by Horvath, who argued that it must be an exotic quark object (Horvath 2012). Our current study strongly supports Horvath’s suggestion, i.e., the planet of PSR J1719-1438 is a possible SQM candidate. It is thus very encouraging that while only five pulsar planets have been detected, we already have one SQM candidate among them. This suggest to us that close-in exoplanets would be a hopeful and powerful tool to test the SQM hypothesis.

4. Detectability of Close-in Pulsar Planets

Searching for close-in exoplanets around pulsars should be the main direction of our future efforts. Due to their extreme closeness, these planets will only exert a very small radial velocity perturbation on the central compact host, which will be difficult to find using pulsar timing observations. Next, we give an estimate on the lower mass limit of the planets, which could be detected with current observational techniques.

Let us consider a planet of mass $m$ orbiting around a pulsar ($M$). In half of the orbital period, the pulsar will have a positive radial velocity perturbation with respect to us, owing to the existence of the small companion, while in the other half orbit, it has a negative velocity perturbation. As a result, the topocentric time-of-arrival (TOA) of its clock-like pulses will systematically deviate from the normal rhythm regularly. The accumulated TOA deviation can be as large as several milliseconds in each half orbit and can be potentially detected through long-term timing observations. In fact, assuming a circular orbit, the planet mass is connected with the semi-amplitude $\Delta t$ of the corresponding TOA variations as (Wolszczan & Frail 1992; Wolszczan 2012)

$$m \sin i \approx 21.3 \, M_\oplus \left( \frac{\Delta t}{1 \text{ ms}} \right) \left( \frac{P_{\text{orb}}}{1 \text{ day}} \right)^{-2/3} \left( \frac{M}{1.4 \, M_\odot} \right)^{2/3},$$

where $P_{\text{orb}}$ is the planet’s orbital period, $i$ is the orbital inclination, and $M_\odot = 6.0 \times 10^{27} \text{ g}$ is the Earth mass.
The pulsar timing method is essentially also trying to measure the radial velocity perturbation. By accumulating the TOA residuals induced by the radial velocity variation in half of the orbit and with the microsecond precision of timing observations, it can equivalently measure the radial velocity perturbation at an unprecedented accuracy of $\sim 1$ cm s$^{-1}$. In contrast, traditional radial velocity measurement through optical spectroscopy can only achieve an accuracy of $\sim 1$ m s$^{-1}$ currently. Timing observation is thus an ideal method that could be effectively used to search for possible close-in strange planets around pulsars.

In view of the radial velocity variation ($\Delta V$) of the host pulsar, Equation (4) can be conveniently expressed as

$$m \sin i \approx (M a / G)^{1/2} \Delta V \approx 0.0034 M_\odot \left( \frac{M}{1.4 M_\odot} \right)^{1/2} \times \left( \frac{a}{10^{10} \text{ cm}} \right)^{1/2} \frac{\Delta V}{1 \text{ cm s}^{-1}},$$

where $G$ is the gravitational constant. Taking $30 \text{ g cm}^{-3}$ as a secure upper limit for the density of typical normal planets, we obtain the critical tidal disruption radius as $r_{\text{td}} \approx 5.6 \times 10^{10} \text{ cm}$ (Section 2). We thus need to search for strange planets with orbital radii smaller than this value. In fact, all of the currently detected exoplanets (except the pulsar planet PSR J1719-1438B) lie far beyond this region (Figure 2). From Equation (5), we see that at the limiting radius ($a \sim 5.6 \times 10^{10} \text{ cm}$), all planets more massive than $\sim 0.008 M_\odot$ can be detected by current pulsar timing observations. For more close-in strange planets, even less massive SQM planets can also be detected. Taking typical values of $i = 45^\circ$, $\Delta V = 1 \text{ cm s}^{-1}$, and $M = 1.4 M_\odot$, we have plotted the limiting mass of planets that could be detected in Figure 4. The figure gives us the encouraging information that close-in strange planets need not be very massive to be detected with our current observational techniques.

Lying in the tidal disruption region for normal matter, these strange planets will also have very small orbital periods. According to Kepler’s law, the radius and period of the orbit are related by

$$\frac{a^3}{P_{\text{orb}}^2} \approx \frac{GM}{4\pi^2}.$$  \hspace{1cm} (6)

At the limiting radius of $r_{\text{td}} \approx 5.6 \times 10^{10} \text{ cm}$, the period is $P_{\text{orb}} \approx 6100 \text{ s}$. For more close-in orbits, the periods will be even smaller. In Figure 5, the relation between $P_{\text{orb}}$ and $a$ is plotted for these close-in orbits. From this figure, we see that in addition to the criterion of $a < 5.6 \times 10^{10} \text{ cm}$, the small orbit period of $P_{\text{orb}} < 6100 \text{ s}$ is another specific feature for SQM planets. PSR J1719-1438B has an orbital radius of $\sim 6 \times 10^{10} \text{ cm}$ and orbital period of 7837 s. Its orbital parameters are slightly above the SQM criteria, but it still can be regarded as a good candidate.

5. Conclusions and Discussion

Discriminating strange stars from neutron stars observationally is an important but challenging problem (Cheng et al. 1998; Xu et al. 2001; Weber 2005; Bauswein et al. 2009; Adriani et al. 2015; Drago & Pagliara 2016). A few possible methods have previously been suggested in the literature, but they are either inconclusive or impractical currently. We here propose a unique method to test the SQM hypothesis: searching for close-in exoplanets with very small orbital radii ($a < 5.6 \times 10^{10} \text{ cm}$) and very small orbital periods ($P_{\text{orb}} < 6100 \text{ s}$). This is based on the fact that SQM planets are extremely compact and can survive even when they are in the tidal disruption region for normal hadronic planets. We have examined all of the detected exoplanets around main-sequence stars and found no clues pointing toward the existence of SQM objects among them. However, the pulsar planet PSR J1719-1438B, which has an orbital radius of $\sim 6 \times 10^{10} \text{ cm}$ and orbital period of 7837 s, is found to be an interesting candidate.

We stress that in the future, such efforts should be made mainly on exoplanets around pulsars, as SQM planets are most likely associated with such compact stars (which themselves should also be strange quark stars in this case). Theoretically, SQM planets can be formed in a few ways. First, at the birth of...
an SQM star (either from the phase transition of a massive neutron star, or from a merger of two neutron stars), plenty of small SQM nuggets should be ejected. These SQM nuggets will “contaminate” the surrounding normal planets and convert them into SQM planets. This means that if the Bodmer–Witten hypothesis is correct so that neutron stars are actually strange stars, then strange planets should also be quite common. Second, SQM clumps of planetary masses may be ejected from a strange quark star at its birth, because the newly formed SQM host star should be hot and highly turbulent, giving birth to high-velocity eddies (Xu & Wu 2003; Horvath 2012). These clumps may finally become planets around the host star due to their deep gravitational potential well. Interestingly, SQM planets formed in this way are most likely close-in, as the ejection may not be too fierce. Third, planetary SQM objects may have been directly formed at an early stage of our universe, i.e., the so-called quark phase stage, when the mean density of the universe was extremely high (Cottingham et al. 1994). Some of these SQM objects may have survived and been captured by compact stars (and even by main-sequence stars) to form planetary systems at later stages. With an unprecedented equivalent radial velocity accuracy of \( \sim 1 \, \text{cm s}^{-1} \), the pulsar timing method could reveal close-in planets as small as \( \sim 10^{-2} \, M_\oplus \). We appeal to radio astronomers to increase attention on searching for such close-in exoplanets in the future. If found, these planets will spur a long-awaited solution for this highly disputed fundamental problem.

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