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Orbital Properties and Gravitational-wave Signatures of Strangelet Crystal Planets

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Abstract

In this paper we consider the possibility that strange quark matter (SQM) may manifest in the form of strangelet crystal planets. These planet-like objects are made up of nuggets of SQM, organized in a crystalline structure. We consider the so-called strange matter hypothesis proposed by Bodmer, Witten, and Terazawa, in that SQM may be the absolutely stable state of matter. In this context, we analyze planets made up entirely of strangelets arranged in a crystal lattice. Furthermore, we propose that a solar system with a host compact star may be orbited by strange crystal planets. Under this assumption we calculate the relevant quantities that could potentially be observable, such as the planetary tidal disruption radius, and the gravitational-wave signals that may arise from potential star–planet merger events. Our results show that strangelet crystal planets could potentially be used as an indicator for the existence of SQM.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739)

1. Introduction

The strange quark matter (SQM) hypothesis, i.e., matter consisting of *up*, *down*, and *strange* quarks in an absolutely stable state of hadronic matter, was proposed by Bodmer, Witten, and Terazawa (Bodmer 1971; Terazawa 1979; Witten 1984). If this hypothesis is true it has implications for cosmology, the early universe and its development to the present day, astrophysical compact objects, and laboratory physics (Crawford et al. 1993; Schaab et al. 1996). Currently, there is no sound scientific basis either confirming or rejecting this hypothesis, so it remains a possibility (Glendenning et al. 1995b; Schaab et al. 1996; Weber et al. 1996). Under this hypothesis compact stars can be considered strange quark stars, self-bound objects composed of SQM, as opposed to traditional, gravitationally bound neutron stars (Witten 1984; Alcock et al. 1986; Haensel et al. 1986; Glendenning 1990). Furthermore, in Witten (1984), Alcock et al. (1986), Haensel et al. (1986), Glendenning et al. (1995a), and Kettner et al. (1995), the authors further developed the concept of strange quark stars, that is, objects consisting of a SQM core surrounded by a nuclear crust. They found a complete sequence of strange stars that range from very compact members, with properties similar to those of neutron stars, to white dwarf-like objects (labeled strange dwarfs), to planetary-like strange matter objects or strange MACHOS. It was pointed out that the minimum-mass configuration in such a sequence is $\sim 0.017 M_{\odot}$, and that such values depend on the chosen value of inner crust density (Glendenning et al. 1995a; Kettner et al. 1995). If abundant enough in our Galaxy, such low-mass strange stars, whose masses and radii resemble those of ordinary planets, could be seen by gravitational microlensing searches (Weber et al. 1996). Furthermore, Alford et al. (2012) performed a study on *strangelet dwarfs*—which consist of a crystalline structure of strangelets in a sea of electrons. In their work, they showed that if the surface tension of the interface between strange matter and the vacuum is less than a critical value, there is, at least, one stable branch in the mass–radius relation for strange stars.

In the work presented here we follow the work of Alford et al. (2012), except we focus on planetary objects, characterized by low pressures. Furthermore, recently there have been great advances in the detection of exoplanets—with a wealth of data available (Perryman 2000; Schneider et al. 2011; Armstrong et al. 2016; Borucki 2016). Recently, Huang & Yu (2017) and Geng et al. (2015) propose the use of such data to search for strange matter planets (in the context defined by Glendenning et al. 1995a; Kettner et al. 1995) by analyzing two possible observational signatures: the tidal disruption radius and the gravitational-wave (GW) emission from a binary system composed of a host compact star and a strange planet. They identified candidates of SQM planets using the following specifications: very small orbital period ($\leqslant$6100 s), an orbital radius smaller than 5.6×10^{10} cm and, possibly strong GW emission by strange planets with masses $\geqslant 10^{-5} M_{\odot}$. The idea is that if any of these planets are, in fact, strange planets, then due to their strange matter properties (increased compactness, for instance) their observational signatures should be different.

In this work we follow in the footsteps of Huang & Yu (2017) and Geng et al. (2015) by searching for signatures of SQM in the observed data of exoplanets. We consider, however, a somewhat more sophisticated model for strange quark planets, one that resembles the actual structure of a planet. We recall that in the original proposal, strange planets were in fact very low-mass strange stars (the order of a few Jupiter masses), with a small seed of strange matter in its core and a relatively large nuclear crust extending all the way to the surface. In our model, as will become clear, we consider the possibility of strangelets forming a crystalline structure such that, as in a white dwarf, the objects are supported against gravitational collapse by electron degeneracy pressure. Differing from a white dwarf (or the crust of neutron stars), in our proposed model instead of ions we have strangelets. Such objects could be formed by the same process that hypothetically generated the compact star host (in a supernova, or stellar merger event, for instance), with the high-density matter giving birth to the high-density strange quark star (composed of homogeneous strange matter) and lower-density lumps, giving rise to crystalline strange planets.

This paper is divided as follows. In Section 2, we describe the microscopic model for strangelet crystal planets, based on the Heiselberg (1993) mass formula for the strangelet considering the screening of electric field, from which we can calculate the equation of state (EoS) of strangelet crystal matter. With the EoS in hand, we compute the structure of the strangelet crystal planets by imposing the appropriate hydrostatic equilibrium conditions. This sequence of planet-like objects is shown in Section 3. In Section 4 we look at the orbital properties of strangelet crystal planets and discuss possible observational implications. Our discussions and conclusions are presented in Section 5.

2. Microscopic Model

According to the SQM hypothesis, matter composed of roughly equal numbers of up (u), down (d), and strange (s) quarks may be more stable than ordinary nuclear matter (Bodmer 1971; Terazawa 1979; Witten 1984). Farhi & Jaffe (1984) have shown, within the framework of the MIT bag model, that for a wide range of parameters (α_c—the strong coupling constant, m_s, the mass of the strange quark and, B, the bag constant) strange matter could indeed be *absolutely* stable. If this is indeed the case, SQM may manifest in a wide range of "sizes," ranging from small *nuggets* with small baryon number A—analogous to nuclei—all the way to bulk matter with very large A—analogous to neutron stars. Based on this idea, Berger & Jaffe (1987) and Farhi & Jaffe (1984) derived a mass formula for drops of strange matter—analogous to the Weizsaecker mass formula for nuclei. Later, this formalism was generalized by the authors of Crawford et al. (1992) and Desai et al. (1993), who included a parameter to take into account the uncertainties in our understanding of surface effects. The mass formula for strangelets was further developed by Heiselberg (1993), who took into account the screening of electric fields. The efforts of Heiselberg (1993) also served as a foundation for Jaikumar et al. (2006), who proposed, for the first time, that strangelets may manifest in a crystalline structure. Here we follow in the footsteps of the aforementioned authors, focusing on the low-pressure regime, which is more appropriate for the planetary objects we seek to study. For our study we have set $m_s = 150$ MeV for strange quark mass and the bag constant is $B^{1/4} = 146.96$ MeV.

As described in Heiselberg (1993) the energy per quarks in a strangelet may be written as

$$E/N = \mu_0 + \frac{E_c + 4\pi\sigma R^2}{4\pi R^3 n/3}, \tag{1}$$

where $\mu_0 = \mu_d = \mu_s = \mu_u$ (due to β equilibrium), R is the strangelet radius, σ is the surface tension, n is the quark density, and E_c is the Coulomb energy. In this work we are interested in crystalline strange matter, thus we need to restrict our study to the low-surface-tension regime. As discussed in Alford et al. (2012) the critical value for the surface tension that allows the formation of a strangelet crystal is ~1–10 MeV fm^{-2}. In this work we use $\sigma = 0.6$ MeV fm^{-2}, which is appropriate for the scenario we are interested in. Note that we have also calculated strangelet properties for $\sigma = 0.2$ and 1.0 MeV fm^{-2}, which did not significantly change the strangelet energy. By providing different values for A we use Equation (19) of Heiselberg (1993) to calculate the charges of different strangelets, whose properties we present in Table 1. The strangelets we use in our study are appropriate to describe the low-pressure/planetary objects we are interested in. As expected, strangelets with higher A have larger masses. Furthermore, the Z/A ratio is small relative to ordinary nuclei, as strangelets are less charged (due to the presence of the negatively charged strange quark; Madsen 1995).

Table 1
Properties of Some Strangelets from Equation (1) for Different Constant Surface Tension Values σ (in MeV fm^{-2})

Label	A	Z	E (10^6 MeV)		
			$\sigma = 0.2$	$\sigma = 0.6$	$\sigma = 1.0$
Stra$_1$	5×10^3	581	4.5189	4.5189	4.5201
Stra$_2$	1×10^4	793	9.0258	9.0277	9.0297
Stra$_3$	5×10^4	1527	45.055	45.060	45.066
Stra$_4$	1×10^5	1986	90.073	90.082	90.091

Once we have calculated the strangelet masses, we use a simplified Wigner–Seitz model, much like in Alford et al. (2012). Thus, we consider a crystal structure of periodic spheres in which each cell of radii R consists of a strangelet residing at its center, surrounded by an electronic cloud. Each cell contains the amount of electrons needed to make it electrically neutral (Shapiro & Teukolsky 2008; Glendenning 2012). Thus, for a given density ρ, the electron density is $\rho_e = (Z/A)\rho$, where A is the mass number of the nuclear species and Z is its atomic number. As we have mentioned before, we are interested in planetary objects characterized by low pressure/density, thus the constant electron density approximation is appropriate (Alford et al. 2012), and we ignore the effect of pressure when calculating the strangelet properties, in particular $Z(A)$. For stellar objects where pressure effects cannot be ignored, one will have Z changing as a function of pressure/density due to electron capture. We can then calculate the contribution of the strangelets, lattice, and electron gas, obtaining the energy density and pressure given by

$$\epsilon(\rho) = \frac{\rho}{A}\left(E - Zm_e - \frac{9}{10}\frac{(Ze)^2}{R}\right) + \epsilon_e(k_e), \tag{2}$$

$$P(\rho) = P_e(k_e) - \frac{3}{10}\left(\frac{4\pi}{3}\right)^{1/3} Z^{2/3} e^2 \rho_e^{4/3}, \tag{3}$$

where E is the mass of the strangelet, e is charge of electrons, and $\epsilon_e(k_e)$ and $P_e(k_e)$ are the energy density and pressure of electrons, respectively (Glendenning 2012). Note that for the low-pressure regime we consider here, the energy density is mostly dominated by the strangelet contribution ($\rho E/A$). The negative term on Equation (3) is the lattice contribution to the total pressure. Furthermore, the third term on Equation (2) represents electrostatic correction to the total energy density. Note that as in Heiselberg (1993) we are using $e^2 = \alpha$, the fine structure constant.

The EoS of such matter is shown if Figure 1, where we show the pressure as a function of energy density for the EoS associated with each of the studied strangelets of Table 1. Such results show that the crystalline matter proposed in this work has relatively low densities and pressure (in particular when compared to other works dealing with SQM (Alford et al. 2012). Note that one gets a finite density at $P = 0$. As discussed in Alford et al. (2012) this corresponds to the energy density of atomic cells, except in this case instead of ordinary atoms we have strangelet atoms, in which case the energy

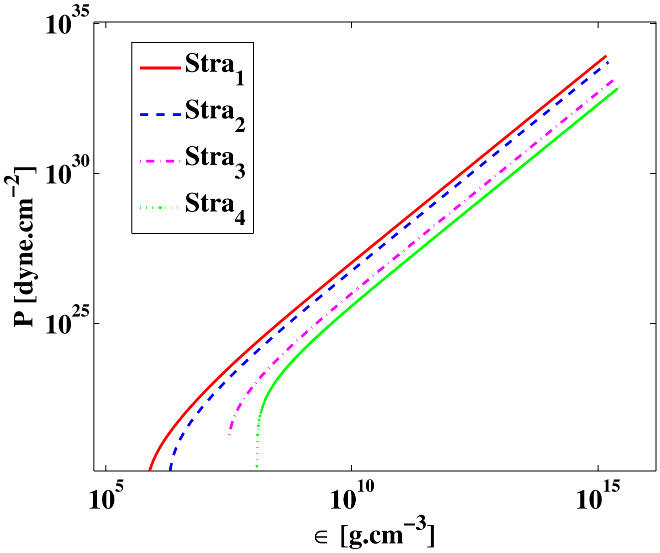

Figure 1. EoSs for strangelet crystal planets made of different strangelet labeled as "Stra" from Table 1 and Equations (2)–(3).

density at $P = 0$ is significantly higher than that of ordinary atoms, which is explained by the fact that "strangelet atoms" have a significantly higher mass ($\sim 10^6$ MeV) than ordinary atoms, such as iron, for instance, whose mass is 52×10^3 MeV. Furthermore, we note that less massive strangelets are associated with "stiffer" EoS, i.e., higher pressures at the same energy density, which can be understood by the Z/A ratio that is much higher for smaller strangelets, thus leading to denser electron gas with a significantly stronger contribution to the pressure.

3. Strangelet Crystal Planets

With the complete description of the microscopic physics (both of the strangelet and of the crystalline strange matter) we now proceed to determine the macroscopic properties of self-gravitating objects. For this study we will consider spherically symmetric geometry, whose metric is given by

$$ds^2 = -e^{2\Phi}dt^2 + e^{2\Lambda}dr^2 + r^2 d\Omega^2, \tag{4}$$

where Φ and Λ are functions of r and, $d\Omega^2 = d\theta^2 + \sin^2\theta d\phi^2$. With the aid of Einstein's equation and assuming that the matter is a perfect fluid, one gets the Tolman–Oppenheimer–Volkoff (TOV) equation, which represents the hydrostatic equilibrium equation for a spherical body (Oppenheimer & Volkoff 1939; Tolman 1939), given by

$$\frac{dp}{dr} = -\frac{(\epsilon(r) + p(r))(m(r) + 4\pi r^2 p(r))}{r(r - 2m(r))}, \tag{5}$$

which needs to be solved in conjunction with the mass continuity equation,

$$\frac{dm(r)}{dr} = 4\pi r^2 \epsilon(r), \tag{6}$$

for a particular, EoS $P = P(\epsilon)$. We now employ the EoS developed in Section 2 for a strangelet crystal configuration, to obtain the macroscopic properties of such objects. Since we are considering a solid, fully crystallized object, we found it appropriate to name them strangelet crystal planets, so as to differentiate them from previous models of strange planets (in which SQM is not crystallized, but present in bulk in a small region of the object's core; Alcock et al. 1986; Alcock & Olinto 1988; Glendenning et al. 1995a; Kettner et al. 1995).

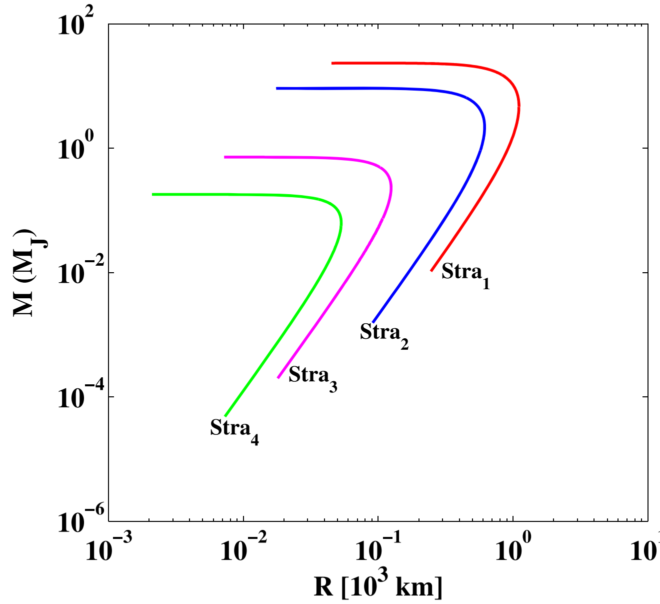

Figure 2. Mass vs. radius of the strangelet crystal planets for different strangelets from Figure 1.

We are interested in the macroscopic properties of the planets, namely mass and radii; this is possible from the solution of TOV's equation, and the EoS given by Equations (2)–(3). This system of differential equations is numerically integrated for a given central energy density ϵ_c from $r = 0$ to $r = R$, where the pressure vanishes, $p(R) = 0$ (planet's surface). Hence, we obtain the radius R and the gravitational mass M of the planet.

The family of strangelet crystal planets is shown in Figure 2 which shows the gravitational mass as a function of radius. Given the planets' low mass and their planetary nature, the mass is given in Jupiter mass units. The results of Figure 2 show that, as expected, a stiffer EoS leads to planetary sequences with higher maximum mass. We can also note that for lower-mass planets associated with smaller central densities, the mass is proportional to R^3, which is typical for planetary objects because they are mostly composed of incompressible matter. An interesting result is that, contrary to what one would expect, crystals made of heavier strangelets lead to a lower maximum mass for planets. Furthermore, for a given mass, planets made of lighter strangelets are larger, which is expected. The reason for such behavior has already been discussed: heavier strangelets have a smaller Z/A ratio, thus they have a less dense electron gas surrounding them, which yields less pressure and hence lower masses.

4. Orbital Properties of Strangelet Crystal Planets

Previous studies have tried to establish a possible connection between strange planets and exoplanets, looking for possible aberrant behavior in observed exoplanets as possible evidence for SQM. Here we follow in the footsteps of Huang & Yu (2017) and Geng et al. (2015) and determine the relevant properties associated with strangelet crystal planets.

Table 2
Properties of Maximum Mass Strangelet Crystal Planets for Each Strangelet Studied

Stra	M (M_J)	R (km)	$\bar{\epsilon}$ (g cm^{-3})	r_{td} (cm)	P_{orb} (ms)
1	23.3	96	2.5×10^{10}	3.8×10^{7}	107
2	9.2	53	5.9×10^{10}	2.8×10^{7}	69.9
3	7.2	8.0	1.3×10^{13}	4.7×10^{6}	4.6
4	0.181	3.65	3.5×10^{12}	7.3×10^{6}	9.0

Note. Each strangelet is labeled by numbers. M_J is Jupiter's mass ($M_J \sim 2 \times 10^{-3} M_\odot$).

Table 3
GW Amplitude for the Crystalline Strange Planet Merger Events at the Distance $d = 10$ kpc

Stra	M (M_J)	R (km)	$\bar{\epsilon}$ (g cm^{-3})	h
1	23.3	96	2.51×10^{10}	3.08×10^{-21}
2	9.2	53	5.87×10^{10}	1.61×10^{-21}
3	7.2	8.0	1.33×10^{10}	7.68×10^{-21}
4	0.181	3.65	3.53×10^{12}	1.24×10^{-22}

Note. The host star has $M_\star = 1.4 M_\odot$.

The first possibility we explore is the orbit of exoplanets. Since strange planets are more compact, they can survive in closer orbits, where traditional hadronic planets would be subject to tidal disruptions. When a planet orbits around its host star, 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 far from each other (Gu et al. 2003). The 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, is defined as (Hills 1975)

$$r_{td} \approx \left(\frac{6M_\star}{\pi \bar{\epsilon}}\right)^{1/3}, \tag{7}$$

where $M_\star$ is the mass of the central host star, and $\bar{\epsilon}$ is the average density of the planet. If the distance is smaller than r_{td}, the tidal force will dominate and the planet will be completely broken up. Equation (7) can be rewritten as

$$r_{td} \approx 1.5 \times 10^{6}\left(\frac{M_\star}{1.4 M_\odot}\right)^{1/3}\left(\frac{\bar{\epsilon}}{4 \times 10^{14}}\right)^{-1/3}. \tag{8}$$

One can also determine the period associated with orbits at the tidal disruption radius. From Kepler's law, the radius and period of the orbit are related by (Huang & Yu 2017)

$$\frac{r^3}{P_{orb}^2} \approx \frac{GM_\star}{4\pi^2}. \tag{9}$$

If we take $\bar{\epsilon} = 30$ g cm^{-3} and $M_\star = 1.4 M_\odot$, the tidal disruption and the orbital period will be: $\sim 5.6 \times 10^{10}$ cm and $\sim$6100 s, respectively. On the other hand, for strange planets, with typical densities $\sim 4 \times 10^{14}$ g cm^{-3}, we will have $\sim 1.5 \times 10^{6}$ cm and ultra-short period $P_{orb} \sim 0.845$ ms. These results show us a possible way to identify SQM planets: if the tidal disruption and orbital period are significantly less than $\sim 5.6 \times 10^{10}$ cm and $\sim$6100 s, respectively, it must be a strange planet (Huang & Yu 2017). With these results, we can apply them to our model.

The orbital properties for the maximum-mass strangelet crystal planets found in our study are shown in Table 2, where we have obtained the tidal disruption r_{td} and P_{orb} from Equations (8) and (9), respectively (using $M_\star = 1.4 M_\odot$). In the table, M is the total mass of the planet, R is the radius, $\bar{\epsilon}$ is the average density, r_{td} is the tidal disruption, and P_{orb} is the orbital period. We note that the tidal disruption and the rotation periods of these planets are, as expected, much smaller than those of ordinary planets (5.6×10^{10} cm; 6100 s). Also, we see that their densities are much higher when compared to ordinary planets ($\sim$1–30 g cm^{-3}).

GW emission also warrants investigation. According to general relativity, the orbital motion of a binary system can lead to GW emission and spiral-in of the system. Geng et al. (2015) showed that due to extreme compactness, strange planets can spiral very close to their host compact stars without being tidally disrupted. These systems could potentially serve as a new source for GWs. GW emission from these events happening in our local universe may potentially be strong enough to be detected by upcoming detectors such as Advanced LIGO (Acernese et al. 2006; Abbott et al. 2009) and the Einstein Telescope (Hild et al. 2008; Punturo et al. 2010).

This analysis can thus be used as possible evidence for the existence of SQM. In contrast to normal matter planets moving around a compact star, their GW signals are negligibly small since the planet cannot get very close to the central star due to the tidal disruption effect.

According to Geng et al. (2015), the strain amplitude of GW from a strange matter system, at the last stage of the inspiraling and at distance d from us, is

$$h = l\left(\frac{M_\star}{1.4 M_\odot}\right)^{2/3}\left(\frac{\bar{\epsilon}}{4 \times 10^{14}}\right)^{4/3}\left(\frac{R}{10^4}\right)^{3}\left(\frac{d}{10}\right)^{-1}, \tag{10}$$

where $l = 1.4 \times 10^{-24}$, d (in kpc) is the distance of the binary to us, and R is the radius of the star (in cm). If r_{td} is too large, the GW emission will be very weak. For example, at $d = 10$ kpc, for a typical planet with $M = 5 \times 10^{-4} M_{Jup}$, $\bar{\epsilon} \sim 10$ g cm^{-3}, and $R \sim 3.6 \times 10^{8}$ cm, disrupted at 5.1×10^{10} cm, the maximum GW amplitude is only $h \approx 4.9 \times 10^{-29}$; screening for high density $\sim$30 g cm^{-3}, the GW amplitude is $h \approx 7.05 \times 10^{-26}$, which is too weak to be detected. For strange planets, however, the strain amplitudes of *GWs* are between $\sim 10^{-23}$ and 10^{-22}, at a distance of $d \sim 10$ kpc (Geng et al. 2015).

We now apply Equation (10) to strangelet crystal planets. We obtain the results shown in Table 3. From this table it is clear that a binary system with strangelet crystal planets can emit GW with amplitudes of the order of $\sim 10^{-22}$–10^{-21} with frequencies ($=2/P_{orb}$) between 15 and 450 Hz. These values are within the sensitivity of GW detectors like Advanced LIGO and the Einstein Telescope (Geng et al. 2015).

Finally, we summarize the properties of strangelet crystal planets and compare them with ordinary planets and strange planets. From Table 4, we see that our model differs from other cases in which they have higher r_{td} and P_{orb} compared to strange planets, and lower r_{td} and P_{orb} compared to ordinary planets. Additionally, strangelet crystal planets and strange planets have the strain amplitude in the same order, whereas ordinary planets have much lower strain amplitudes than other SQM objects.

Table 4
Comparisons: Strangelet Crystal Planets vs. Ordinary Planets and Strange Planets

Object Planets	$\bar{\epsilon}$ (g cm^{-3})	$r_{\rm td}$ (cm)	$P_{\rm orb}$ (s)	h
Ordinary Planets				
Low density	10	5.1×10^{10}	∼5263	4.9×10^{-29}
High density	30	5.6×10^{10}	∼6100	7.1×10^{-26}
Strangelet Crystal Planets	$\sim 10^{10}$–10^{12}	$\sim 4 \times 10^{6}$–3×10^{7}	∼0.009–0.107	$\sim 10^{-22}$–10^{-21}
Strange Planets	$\sim 4.0 \times 10^{14}$	$\sim 1.5 \times 10^{6}$	$\sim 8.45 \times 10^{-4}$	$\sim 10^{-23}$–10^{-21}

5. Discussion and Conclusions

In this work we have proposed a novel planetary configuration: strangelet crystal planets are low-pressure objects made up of strangelets arranged in periodic crystals (Shapiro & Teukolsky 2008; Glendenning 2012). This model differs from previously proposed strange star models (Alcock et al. 1986; Alcock & Olinto 1988; Glendenning 1990; Glendenning & Weber 1992; Glendenning et al. 1995a; Kettner et al. 1995) in that in those models SQM is found in bulk and possibly surrounded by ordinary hadronic matter. In our study we follow the approach of Jaikumar et al. (2006) in which SQM takes a crystalline form. Within such a scenario, self-bound strangelets can organize themselves in a crystal lattice, permeated by electron gas (needed for charge neutrality); such matter could then form self-gravitating objects supported against gravitational pull by the electronic pressure, much like the white dwarfs do.

We have determined the masses and radii of such objects and found that their mass may be as high as that of ordinary planets ($\sim 10^{-4}$–$25\,M_J$), but with slightly smaller radii than ordinary planets. Furthermore, we have calculated possible observable signatures of such a model using the concept of tidal disruption radius and amplitude of GWs that could be emitted by such systems. As expected we have found that due to their compactness, the tidal disruption radii of strangelet crystal planets are significantly smaller than those of ordinary planets. We have found, however, that when compared to previously proposed strange planet models, our scenario leads to higher tidal disruption radii. This means that strangelet crystal planets exhibit an intermediate behavior with possible orbital properties not as extreme as those of strange planets but not as mild as those of ordinary planets. This is not surprising given the *"hybrid"* nature of our proposal, which mixes properties of both traditional planets (solid, crystalline structure) with that of strange planets (SQM). As for the possibility of GW emission, we have found that our model does not differ significantly from the previously proposed strange planets, with the amplitude of GW from both models being somewhat similar. However, both models predict a GW amplitude significantly higher than that of ordinary planets, which could potentially be detected by the future Einstein Telescope or the Advanced LIGO (Geng et al. 2015), providing, if detected, evidence for SQM in the form of a strange solar system.

Our assumptions for the existence of strangelet crystal planets are based on the following possible scenarios: first, after the birth of strange quark stars (hot and highly turbulent environment), they may eject low-mass quark nuggets. It has been suggested that ejection of planetary clumps may happen simultaneously due to the strong turbulence of the strange star surface (Ren-Xin & Fei 2003; Xu 2006; Horvath 2012). Thus, the strange planetary system can form directly. Second, the contamination processes during the supernova explosion that give birth to a strange star, if the planets of the progenitor star can survive the violent process, may be contaminated by the abundant strange nuggets ejected from the new strange star and then converted to strange planets (Wolszczan & Frail 1992; Geng et al. 2015). If these planets are remnants of the progenitor star, then there is a possibility that they can be strange planets (Friedman & Caldwell 1991; Kettner et al. 1995; Madsen 1999). Third, stellar and planetary strange matter objects could be a remnant of a quark phase in the primordial universe, which may have survived until now (Cottingham et al. 1994); such objects could be very numerous and they can be captured by strange stars (or neutron stars) to form planetary systems (Chandra & Goyal 2000). Finally, it was suggested in Friedman & Caldwell (1991) that a high enough cosmic-ray flux of strangelets, produced by strange star mergers, would imply that all neutron stars should be strange stars, as they would have been contaminated by the influx of strangelets. More recently, Bauswein et al. (2009) performed a series of simulations in which they found that this implication (contamination of all NS by strangelets) depends on the value of the bag constant, with smaller values ($B \sim 60\,\mathrm{MeV\,fm^{-3}}$) associated with higher strangelet fluxes. Thus, the existence of neutron stars is unlikely. Higher values of B ($\sim 80\,\mathrm{MeV\,fm^{-3}}$), however, lead to smaller fluxes, thus allowing for the coexistence of neutron and strange stars. In relation to our work, where we have adopted $B \sim 60\,\mathrm{MeV\,fm^{-3}}$, this means that in our scenario, most likely, neutron stars would all be strange stars. There are some caveats, however. Unlike the work of Bauswein et al. (2009), where they have set $m_s = 100\,\mathrm{MeV}$, we have used $m_s = 150\,\mathrm{MeV}$, although we believe that this unlikely to qualitatively change the results; second and more importantly: such conclusions are only valid if the strange star mergers are the only source of strangelet ejection, as pointed out in Bauswein et al. (2009).

We intend to pursue further the idea of strangelet crystal planets by adding further sophistication to the model, like a better description of curvature and surface tension effects, exploring their transport and thermal properties, and studying their seismic properties. We are currently investigating the effects of different values for the bag constant on the properties of these objects; this would allow us to investigate the small strangelet flux scenario, as discussed in Bauswein et al. (2009), in which neutron stars and strange stars could potentially coexist. Nonetheless, we believe that the idea set forth in this work introduces interesting possibilities to the already rich study of strange planets and their possible observable signatures.

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