

COALESCENCE OF STRANGE-QUARK PLANETS WITH STRANGE STARS: A NEW KIND OF SOURCE FOR GRAVITATIONAL WAVE BURSTS

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ABSTRACT

Strange-quark matter (SQM) may be the true ground state of hadronic matter, indicating that the observed pulsars may actually be strange stars (SSs), but not neutron stars. According to the SQM hypothesis, the existence of a hydrostatically stable sequence of SQM stars has been predicted, ranging from 1 to 2 solar mass SSs, to smaller strange dwarfs and even strange planets. While gravitational wave (GW) astronomy is expected to open a new window to the universe, it will shed light on the search for SQM stars. Here we show that due to their extreme compactness, strange planets can spiral very close to their host SSs without being tidally disrupted. Like inspiraling neutron stars or black holes, these systems would serve as new sources of GW bursts, producing strong GWs at the final stage. The events occurring in our local universe can be detected by upcoming GW detectors, such as Advanced LIGO and the Einstein Telescope. This effect provides a unique probe to SQM objects and is hopefully a powerful tool for testing the SQM hypothesis.

Key words: gravitational waves – planet–star interactions – stars: neutron

1. INTRODUCTION

With the operational and upcoming detectors, gravitational wave (GW) astronomy is expected to open a new window into the universe in the near future. The last stage of inspiraling neutron stars/black holes provides us with, hopefully, a new candidate for GW sources (Cutler et al. 1993; Del Pozzo et al. 2013). The Advanced LIGO (Acernese et al. 2006; Abbott et al. 2009) detectors will be able to see inspiraling binaries made up of two $1.4 M_{\odot}$ neutron stars to a distance of 300 Mpc. This horizon distance would even be pushed to 3 Gpc by the future Einstein Telescope (Hild et al. 2008; Punturo et al. 2010). In addition to these most promising candidates, people are eagerly looking for other potential GW sources. For a normal-matter planet moving around a compact star, the GW power is negligibly small since the planet cannot get very close to the central star as a whole due to the tidal disruption effect. However, we argue that for a strange-quark matter (SQM) planet orbiting around a strange star (SS), the corresponding GW signals can reach detectable levels. This is basically because the strange-matter planet can get very close to the central compact star without being tidally disrupted due to its extreme compactness.

The existence of strange planets is based on a long-standing theory. It has long been proposed that SQM may be the final ground state of hadronic matter (Itoh 1970; Bodmer 1971; Farhi & Jaffe 1984; Witten 1984). Ordinary nuclei, made up of up and down quarks, may dissolve their boundaries and transit to an SQM phase (consisting of up, down, and strange quarks) if the nuclei experience high-enough pressure. Strange matter in bulk is stable. Even small chunks of strange matter with baryon number lower than 10^7 , called “strangelets,” can be stable due to surface tension. If the SQM hypothesis is correct, then all observed pulsars may actually be SSs but not neutron stars, due to the contamination process by strange nuggets in the universe (Alcock et al. 1986). SSs can exist in various forms, such as bare SSs or SSs with a normal baryonic crust.

Unlike neutron stars, which have a critical mass (Chandrasekhar 1964), there is no minimum mass for SSs. Using the equation of state for SQM from phenomenological models, some authors have predicted the existence of a hydrostatically stable sequence of SQM stars, ranging from strange dwarfs to SSs (Glendenning et al. 1995a, 1995b, Vartanyan et al. 2014). It is interesting to note that strange planets exist in this continuous sequence.

How can strange-matter objects be identified or the SQM hypothesis be tested? Currently, several possible ways have been proposed. According to the equation of state of SQM in the MIT Bag model (Farhi & Jaffe 1984; Krivoruchenko & Martem’ianov 1991; Madsen 1999), the mass–radius relation for SSs follows $M \propto R^3$ if $M < 1 M_{\odot}$, very different from $M \propto R^{-3}$ for neutron stars. Unfortunately, for SSs and neutron stars with the same mass of $\sim 1.4 M_{\odot}$, their radii are similar. Observations show that the average mass of pulsars is around $1.4 M_{\odot}$ (Lattimer & Prakash 2007), consequently leading to the limitation of this method (Pani et al. 2000). Later, it has been argued that the high cooling rate of SQM together with the quick thermal response of the thin crust yields low surface temperatures of SSs as compared to neutron stars of the same age (Pizzochero 1991). However, the cooling rate of neutron stars could also be high after considering more details (Page & Applegate 1992; Lattimer et al. 1994), reducing the temperature differences between the two kinds of objects. Noting the larger shear and bulk viscosities in SSs, some researchers also suggested that they can spin more rapidly, closely approaching the *Kepler* limit (Frieman & Olinto 1989; Friedman et al. 1989; Glendenning 1989). If the spin period of a young pulsar is less than 1 ms, then it is very likely to be an SS rather than a neutron star (Kristian et al. 1989). But these fast spinning objects themselves are difficult to be detected observationally. Researchers also noticed GWs as a possible tool for probing SSs. As rotating relativistic stars, SSs can emit GWs due to normal mode or *r*-mode oscillations (Madsen 1998; Lindblom

& Mendell 2000; Andersson & Kokkotas 2001; Andersson et al. 2002) or global solid deformation (Jaranowski et al. 1998; Jones & Andersson 2002). However, these GWs are generally very weak and the difference between SSs and NSs is even smaller. It is interesting to note that an upper limit of 10^{-24} for the GW strain amplitude has been obtained for 28 known pulsars (Abbott et al. 2005). Also, GW signals of SS mergers may differ slightly from those of neutron star mergers (Bauswein et al. 2010; Moraes & Miranda 2014), but the difference is also difficult to measure. In short, despite long and extensive investigations, the task of identifying strange-matter objects or testing the SQM hypothesis still remains a challenge for researchers hitherto.

In this work, we study the last stage of the inspiraling of a strange-matter planet toward an SS. Very different from what happens in the counterpart of a neutron star planetary system, the strange planet can get very close to the host SS without being tidally disrupted, forming a minitype double compact star system. As a result, an imminent GW burst will be generated due to the final merge. We show that GW emission from these events happening in our local universe is strong enough to be detected by upcoming detectors such as Advanced LIGO and the Einstein Telescope. Such an effect can be used as a unique probe for the existence of SQM stars.

2. GWS FROM MERGING SQM STARS/PLANETS

2.1. Strain Amplitude Evolution

Let us consider a binary system composed of two members with masses M and m , respectively. For simplicity, we assume that the primary compact star has a mass of $M = 1.4 M_\odot$ and the companion star is a planet so that $m \ll M$. The GW radiation power from this binary system is then

$$P = \frac{32G^4 M^2 m^2 (M + m)}{5c^5 a^5}, \quad (1)$$

where G is the gravitational constant, c is the light velocity, and a is the semimajor axis. The measurable signals of GWs are the amplitudes of two polarized components— h_+ and h_\times . For merging binaries, we assume the waves to be sinusoidal and define an effective strain amplitude as $h = (\langle h_+^2 \rangle + \langle h_\times^2 \rangle)^{1/2}$. After averaging over the orbital period, we obtain (Peters & Mathews 1963; Press & Thorne 1972; Postnov & Yungelson 2014)

$$h = 5.1 \times 10^{-23} \left(\frac{\mathcal{M}}{1 M_\odot} \right)^{5/3} \left(\frac{P_{\text{orb}}}{1 \text{ hr}} \right)^{-2/3} \left(\frac{d}{10 \text{ kpc}} \right)^{-1}, \quad (2)$$

where $\mathcal{M} = (Mm)^{3/5}/(M + m)^{1/5}$ is the chirp mass, P_{orb} is the orbital period, and d is the distance of the binary to us.

If the planet is a normal-matter one, the GW signals will always be extremely weak because the planet cannot come very close to the compact primary star. The strong tidal force from the central object will disrupt the planet when it is still far away. Assuming a density of ρ_0 , a normal planet will be disrupted at the distance of

$$r_{\text{td}} \approx 5.1 \times 10^{10} \left(\frac{M}{1.4 M_\odot} \right)^{1/3} \left(\frac{\rho_0}{10 \text{ g cm}^{-3}} \right)^{-1/3} \text{ cm}. \quad (3)$$

r_{td} is usually called the tidal disruption radius. If r_{td} is too large, the GW emission will be very weak. For example, for a normal planet of $m = 10^{-6} M_\odot$ (with density $\rho_0 \sim 10 \text{ g cm}^{-3}$ and radius $R \sim 3.6 \times 10^8 \text{ cm}$) disrupted at $5.1 \times 10^{10} \text{ cm}$, the maximum GW amplitude is only $h \approx 4.9 \times 10^{-29}$ (with a very low frequency of $3.8 \times 10^{-4} \text{ Hz}$) at a distance of 10 kpc, which is too weak to be detected. Even for a giant normal-matter planet of $m = 10^{-3} M_\odot$, the maximum GW amplitude is again only $h \approx 4.9 \times 10^{-26}$, which is still far beyond the detection limit.

However, when the companion is a strange-matter planet, things will become very different. According to the canonical MIT Bag model for SQM, the mass–radius relation of SSs can be well described by $m \propto R^3$. This relation applies to the whole sequence of bare SSs, including strange planets. The extreme high density (typically $\rho_0 = 4.0 \times 10^{14} \text{ g cm}^{-3}$) of strange planet ensures that it can come very close to the compact host star while retaining its integrity because the tidal disruption radius now becomes $r_{\text{td}} = 1.5 \times 10^6 \text{ cm}$. This will give birth to a minitype double compact star system, which will be very efficient in producing GWs. At the last stage of the inspiraling (i.e., when the planet approaches the tidal disruption radius, r_{td}), the strain amplitude of GWs from a strange-matter binary system is

$$h = 1.4 \times 10^{-24} \left(\frac{M}{1.4 M_\odot} \right)^{2/3} \left(\frac{\rho_0}{4.0 \times 10^{14} \text{ g cm}^{-3}} \right)^{4/3} \times \left(\frac{R}{10^4 \text{ cm}} \right)^3 \left(\frac{d}{10 \text{ kpc}} \right)^{-1}. \quad (4)$$

According to this equation, the strain amplitude of GWs from a strange planet of mass $m = 10^{-4} M_\odot$ ($R = 5.0 \times 10^4 \text{ cm}$, $\rho_0 = 4.0 \times 10^{14} \text{ g cm}^{-3}$) will be 1.7×10^{-22} at a distance of $\sim 10 \text{ kpc}$ from us. This amplitude is comparable to that of a neutron star–neutron star binary system (when the orbital period is around 1 s) at $\sim 1 \text{ Mpc}$. So, such SS–strange planet systems would be appealing targets for the ongoing and upcoming GW experiments, such as Advanced LIGO and the Einstein Telescope.

Since the inspiraling is a gradual process during which the strange planet approaches the central SS progressively, we need to consider the evolution of the GW amplitude over the whole procedure. Assuming that the orbit always remains circular, the emission power of GWs can be calculated according to Equation (1). We can then easily know how quickly the orbit shrinks and how the GW amplitude evolves. In Figure 1, the evolution of h during the inspiraling is illustrated (assuming a distance of 10 kpc from us), with three different masses assumed for the strange planets. Correspondingly, the evolution of the GW frequency ($f = 2/P_{\text{orb}}$) is also shown in the lower panel. In our calculations, in order to focus on the last stage of the coalescence, we have taken $20 r_{\text{td}}$ as the initial separation between the two objects. Note that the GW emission is usually very weak and also evolves very slowly when $r < 20 r_{\text{td}}$. It can be clearly seen that in all these cases, the GW signal can rise to a high level at the last stage of the coalescence process. For example, in the $m = 10^{-6} M_\odot$ case, h can remain larger than 10^{-24} for a long time, 3500 s. The GW frequency of these systems is also in the most sensitive range of LIGO and the Einstein Telescope, making them very appealing GW sources.

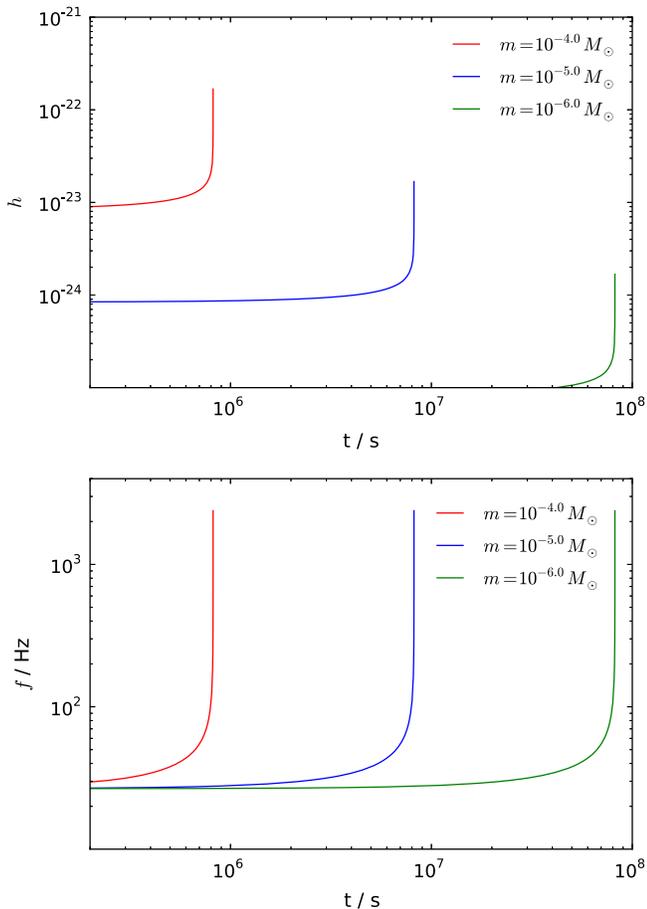


Figure 1. Evolution of GW amplitude (upper panel) and frequency (lower panel) for coalescing strange star–strange planet systems at a distance of 10 kpc from us. The host strange star has a mass of $1.4 M_{\odot}$. The orbits are assumed to be circular, and the initial separation of the two objects is set to be $20 r_{\text{td}}$ (r_{td} is the tidal disruption radius). The solid red, blue, and green lines correspond to strange planets with a mass of 10^{-4} , 10^{-5} , and $10^{-6} M_{\odot}$ respectively. For all the strange planets, a mean density of $\rho_0 = 4.0 \times 10^{14} \text{ g cm}^{-3}$ has been taken. In all the cases, we stop our calculations at the tidal disruption radius, which gives the highest GW amplitude and also the highest GW frequency at the end point of each curve.

2.2. Strain Spectral Amplitude

To judge whether the GWs could be detected by GW experiments, it is useful to plot it against the sensitivity curve. This is usually done by considering the strain spectral amplitude (h_f), which is defined as the square root of the power spectral density, i.e., the power per unit frequency. For the double compact star systems studied here, the Fourier transform of $h(t)$ can be found when f changes slowly (Finn & Chernoff 1993; Nissanke et al. 2010; Postnov & Yungelson 2014), which is

$$h_f = 6.4 \times 10^{-21} \left(\frac{\mathcal{M}}{1 M_{\odot}} \right)^{5/6} \left(\frac{f}{300 \text{ Hz}} \right)^{-7/6} \times \left(\frac{d}{10 \text{ kpc}} \right)^{-1} \text{ Hz}^{-1/2}. \quad (5)$$

Using this stationary phase approximation, the strain spectral amplitude against frequency is plotted in Figure 2, together

with the sensitivity curves of Advanced LIGO and the Einstein Telescope. It can be clearly seen that the GW signals from the coalescing SS systems in our Galaxy (with the planet mass larger than $\sim 10^{-9} M_{\odot}$) can be well detected by these experiments. More encouragingly, the horizon distance of the Einstein Telescope to these events (assuming $m \geq 10^{-5} M_{\odot}$) will even be ~ 3 Mpc, which means the mergers happening in nearby galaxies will also be spotted.

It is interesting to note that high quality GW observations of binary compact star coalescences can directly provide their distance information (Schutz 1986; Messenger & Read 2012), because both the GW amplitude and the frequency evolution can be measured during the inspiraling process. On the other hand, the distance may also be determined by electromagnetic observations on the counterparts, since the coalescence is likely to lead to a strong hard X-ray burst (Huang & Geng 2014). In the future, if a GW signal of an appropriate amplitude is detected from our local universe, it would most likely come from the merger of a strange planet with its host SS (if it also happened in our local universe, the GWs from a double neutron star system will be much stronger and easier to discriminate; see Figure 3). It then can be regarded as a strong proof for the existence of SQMs.

3. CONCLUSIONS AND DISCUSSION

In this study, we have calculated the GW signals from SS–strange planet systems during the final inspiraling phase. The high density of the strange-matter planet ensures it survives tidal disruption and comes very close to the compact central star, leading to strong GW emission. Our results indicate that strange planets with $m \geq 10^{-5} M_{\odot}$ can result in GW outbursts detectable by the future Einstein Telescope up to a horizon of 3 Mpc. These events comprise a completely new kind of GW source, which, if detected, will be strong evidence supporting the SQM hypothesis.

Our calculations are based on the assumption of the existence of SS–strange planet systems. There are at least three possible scenarios in which such systems may be generated. First, newly born strange-quark stars are likely to be hot and highly turbulent. They may eject low-mass quark nuggets. It has been suggested that ejection of planetary clumps may happen simultaneously during the formation of an SS due to strong turbulence on the surface (Xu & Wu 2003; Xu 2006; Horvath 2012). If the ejected strange-quark planet is somehow gravitationally bound, then a strange planetary system can be directly formed. In this case, a convective velocity larger than 10^9 cm s^{-1} on the surface would be needed for the ejection. Second, another possible scenario involves the contamination processes. During the supernova explosion that gives birth to an SS, if the planets of the progenitor star can survive the violent process (i.e., they do not escape or are not vaporized), then they may be contaminated by the abundant strange-quark nuggets ejected from the newly born SS and be converted to strange planets. In fact, two planets of a few Earth-mass have been confirmed orbiting around the pulsar PSR B1257+12 (Wolszczan & Frail 1992). If these planets are remnants of the progenitor star, then the possibility that they have been contaminated and converted to strange planets cannot be excluded currently (Caldwell & Friedman 1991; Glendenning et al. 1995a; Madsen 1999). Finally, according to the big bang

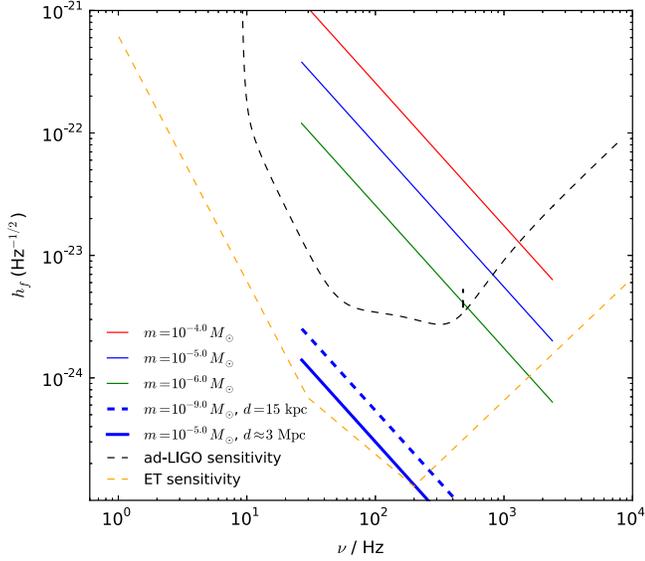


Figure 2. Strain spectral amplitude of the GWs against frequency for coalescing strange star–strange planet systems. The host strange star has a mass of $1.4 M_{\odot}$. The straight red, blue, and green solid lines correspond to strange planets with a mass of 10^{-4} , 10^{-5} , and $10^{-6} M_{\odot}$ respectively, with the system lying at a distance of 10 kpc from us. In these cases, we stop our calculations at the tidal disruption radius, which gives the highest GW frequencies at the end point of each curve. The thick blue dashed line corresponds to a strange planet mass of $10^{-9} M_{\odot}$ and with the system 15 kpc from us. The thick blue solid line corresponds to a strange planet mass of $10^{-5} M_{\odot}$, but with the system residing at a distance of 3 Mpc. The results are compared with the sensitivity curves of Advanced LIGO (the dashed black curve; Harry 2010) and the future Einstein Telescope (the dashed orange curve; Hild et al. 2008).

theory, our universe once experienced a so-called quark phase stage, during which the density and temperature were both extremely high. Planetary strange-matter objects may be directly formed at that stage and may be surviving up to now (Cottingham et al. 1994). Such objects could be very numerous and make up the dark objects in galactic halos (Chandra & Goyal 2000). They can be captured by SSs or neutron stars to form planetary systems.

It is interesting to know how many GW bursts from strange planetary systems could be observed by future GW telescopes each year. Following the idea that SQMs are the final ground state of hadronic matter, we assume that all neutron stars are truly SSs. It is estimated that there are about 10^9 NSs in our Milky Way Galaxy (Timmes et al. 1996), so we take this number as the total amount of SSs in our Galaxy. From a conservative view, planetary systems appear to occur in around 10^{-3} of pulsars (Wolszczan & Frail 1992; Greaves & Holland 2000). Thus the number of strange planetary systems in our Galaxy could be $\sim 10^9 \times 10^{-3} \sim 10^6$. On the other hand, it has been argued that planets around a compact star may collide with each other, generating some large fragments that can fall onto the central compact star. This mechanism has been suggested to account for the bursts from some soft gamma repeaters (Katz et al. 1994). According to Katz et al. (1994), the generated solid bodies can be in the mass range of 10^{22} – 10^{25} g. In our study, in order for the GW bursts to be detectable within our Galaxy, the solid body should be larger than $\sim 10^{24}$ g (or $\sim 10^{-9} M_{\odot}$; see Figure 2). Following the derivations of Katz et al. (1994), the timescale for a single planetary system to undergo such a collision is then $\sim 10^5$ yr. Finally, we estimate that $\sim 10^6/10^5 = 10$ coalescence events could be detected as GW bursts by the future Einstein Telescope. Additionally,

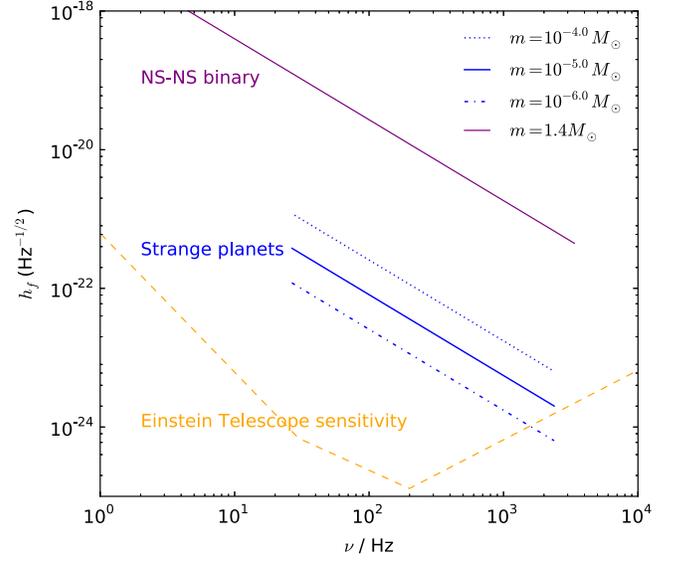


Figure 3. Strain spectral amplitude of the GWs vs. frequency for different binary compact star systems. For strange star–strange planet systems (blue lines), three different planet masses are assumed. The distance is taken to be 10 kpc from us. As a direct comparison, we also plot the case of a double neutron star system (the purple line), again residing at 10 kpc. In all the cases, we stop our calculations at the tidal disruption radius, which gives the highest GW frequency at the end point of each curve. The sensitivity curve of Einstein Telescope is shown by the dashed orange curve. It can be seen that the GW emission from a double neutron star system (with two compact stars that are both about $1.4 M_{\odot}$) are much stronger than a strange star–strange planet system at the same distance. Thus these two kinds of GW sources can be easily discriminated observationally.

Figure 2 clearly shows that the horizon distance for some large strange planets can be as far as a few Mpc. Thus many coalescence events in our local universe (from other nearby galaxies) will also be detectable. So, we believe that the derived event rate of about 10 yr^{-1} is still the lower limit.

Finally, it is worthy to note that many low-mass black hole binary systems may exist in our Milky Way and nearby galaxies (Nakamura et al. 1997). These systems can also merge and give birth to GW bursts with amplitudes similar to the events discussed here. Several methods may help us to discriminate these two kinds of GW sources. First, the chirp mass of an SS–strange planet system is usually much smaller than that of typical low-mass black hole binaries. So the chirp mass measured from the GW signals can help to distinguish them. Second, some forms of hard X-ray bursts may be associated with the coalescence of SS–strange planet systems and can be basically observed, while no significant electromagnetic emission is expected from the mergers of low-mass black holes. Finally, for the SS–strange planet system, the SS can be observed as a pulsar before the coalescence. After the coalescence, the SS is retained and it still can show up as a pulsar. However, for a low-mass black hole binary, no electromagnetic counterpart can usually be directly detected before and after coalescence.

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