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Gravitational wave radiation from a double white dwarf system inside our galaxy: a potential method for seeking strange dwarfs

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Abstract Like the investigation of double white dwarf (DWD) systems, strange dwarf (SD) – white dwarf (WD) system evolution in Laser Interferometer Space Antenna (LISA)'s absolute amplitude-frequency diagram is investigated. Since there is a strange quark core inside an SD, SDs' radii are significantly smaller than the value predicted by the standard WD model, which may strongly affect the gravitational wave (GW) signal in the mass-transferring phases of binary systems. We study how an SD-WD binary evolves across LISA's absolute amplitude-frequency diagram. In principle, we provide an executable way to detect SDs in the Galaxy's DWD systems by radically new windows offered by GW detectors.

Key words: accretion, accretion disks — binaries: close — dense matter — gravitational waves

1 INTRODUCTION

Strange dwarfs are a new kind of celestial object proposed in the 1990s (Weber et al. 1996; Fridolin 2001). They have strange matter cores and crusts made from ordinary matter which is the same as that of a white dwarf. Because of the ultracompact core, strange dwarfs are much denser than white dwarfs. Since some parameters of the equation of state (EOS) of strange quark matter are still uncertain, the exact mass-radius relationship of strange dwarfs is unknown. Hence, observations of strange dwarfs can be used to verify the theory about strange quark matter. In this paper, we propose a new way that can be used to detect the existence of strange dwarfs in compact binary systems by observing their gravitational signals.

Mathews et al. (2006) summarized a number of nearby white dwarfs. Among the sample of 22, the masses and radii of three of them exactly coincide with the theoretical mass-radius relationship of strange dwarfs. They also showed that the latter are more likely to be strange dwarfs rather than white dwarfs with heavy elements. If the results are true, it is reasonable to say that a significant percentage of the white dwarf population should be made up of strange dwarfs. Also, since double white dwarf systems are common in the Galaxy, there should be a considerable number of strange dwarfs existing in compact binary systems.

The Galactic double white dwarf population forms a confusion limited background for Laser Interferometer Space Antenna (LISA) (Schneider et al. 2001), which limits the sensitivity of LISA to some extent, but Nelemans et al. (2001) show that there are a large number of compact binaries, the majority of which are double white dwarf binaries, that are detectable and capable of being resolved by LISA. Therefore, it is possible to observe individual binaries made up of strange dwarfs and white dwarfs. Every gravitational radiation source corresponds to a point on LISA's $\lg h$-$\lg f$ diagram, or $\lg rh$-$\lg f$ diagram, where f is the frequency of the gravitational wave, h is the amplitude and rh is the absolute brightness of the source. Kopparapu & Tohline (2007) made an analogy between the latter and the color-magnitude diagram often used in stellar physics. By knowing a binary system's position on the absolute amplitude-frequency diagram, we can gain information about the physical properties of the components and its evolutionary status. Based on this idea, we proposed that LISA' s amplitude-frequency diagram can serve as a way to distinguish an strange dwarf (SD)-white dwarf (WD) system from other binary systems, such as a double white dwarf system.

2 EVOLUTION OF AN SD-WD SYSTEM

To investigate how an SD-WD system evolves across LISA' s $\lg rh$-$\lg f$ diagram, here we use a simplified binary model to study the different evolutionary states. Our model is based on the following assumptions: the orbit is circular; the motion of the binary is described by Newtonian theory, which means no general relativistic correction is involved; the spin of each star is ignored so that the total angular momentum equals the orbital angular momentum; the tidal effect on the motion of the system and structure of each component is also neglected; the total mass is conserved; angular momentum is lost only via gravitational radiation. Admittedly, a more thorough analysis would be meaningful and even necessary in certain cases, but in this paper, we only use this simplified model to derive a general picture of how an SD-WD system evolves across the amplitude-frequency diagram.

2.1 Star Model

The mass-radius relationship for zero temperature white dwarfs is (Kopparapu & Tohline 2007)

$$R = 0.0114 R_s \times \left[\left(\frac{M}{M_{\rm ch}}\right)^{-\frac{2}{3}} - \left(\frac{M}{M_{\rm ch}}\right)^{\frac{2}{3}}\right]^{\frac{1}{2}} \times \left[1 + 3.5\left(\frac{M}{M_p}\right)^{-\frac{2}{3}} + \left(\frac{M}{M_p}\right)^{-1}\right]^{-\frac{2}{3}}, \tag{1}$$

where $M_p = 0.000396\,M_{\rm ch}$, $M_{\rm ch}$ is the Chandrasekhar mass, which is about 1.44 solar masses, M_p is a constant, with a very small numerical value. Since there is no analytic form for the mass-radius relationship of strange dwarfs, we will use the data calculated by Vartanyan et al. (2004). Here, we adopt the first model with the bag constant $B = 50\,\mathrm{MeV\ fm}^{-3}$. The mass-radius relationships of strange dwarfs with different bottom densities are plotted in Figure 1 and that of white dwarfs is also shown for comparison. As we can see, the curves for strange dwarfs with different configurations deviate significantly from that of white dwarfs. However, the mass-radius relationships of strange dwarfs are quite similar, only differing from each other when the mass is very low. Considering that our binary model is very simple, which configuration is adopted will make a minor difference in our final results. In this paper, the configuration with bottom density equaling the neutron drip density is used. Of course, a comprehensive analysis will lead to insightful results if the binary model is accurate enough.

2.2 Evolution of the System

A detached SD-WD system loses its angular momentum due to gravitational radiation, and thus the components spiral inward and the orbital frequency gets smaller. This is the so-called in-spiral phase. It will last until one of the components fills its Roche lobe and mass transfer begins. Because of mass transfer from the donor to the accretor, both the radius of the donor and the radius of its Roche lobe will change. If the star's size increases faster than that of its Roche lobe, the mass transfer rate will become faster and faster. This kind of mass transfer phase is unstable and it will not last long. On the other hand, if the star's size increases more slowly than that of its Roche lobe, the surface of the star will marginally touch the edge of its Roche lobe due to gravitational radiation. This kind of mass transfer phase is stable. It should be pointed out that, compared with the unstable mass transfer phase, the in-spiral phase and stable mass transfer phase are long-lived and the time scale is determined by the rate at which angular momentum is being lost due to gravitational radiation. Therefore, the population of SD-WD systems should be dominated by systems in the in-spiral phase and those in the stable mass-transfer phase.

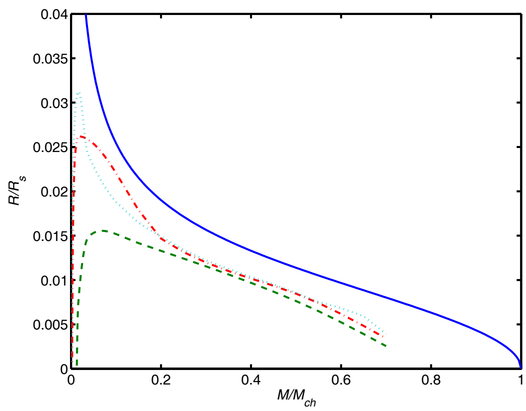

Fig. 1 Mass-radius relationship for strange dwarfs and white dwarfs. Here we choose the Chandrasekhar mass as the mass unit and the solar radius as the length unit. Solid line: white dwarf; Dashed line: strange dwarf with $\rho_{\rm cr} = 4.3 \times 10^{11}$ g cm^{-3}; Dot-dash line: strange dwarf with $\rho_{\rm cr} = 4.3 \times 10^{10}$ g cm^{-3}; Dotted line: strange dwarf with $\rho_{\rm cr} = 4.3 \times 10^{9}$ g cm^{-3}.

In the following, for a particular SD-WD system, we will decide which component will be the donor after the in-spiral phase; and we also need to know whether this system will evolve into an unstable or stable mass transfer phase. The criteria are shown below. The subscript sd stands for strange dwarf, wd for white dwarf and l for Roche lobe; we define mass ratio as $q \equiv \frac{M_{\rm sd}}{M_{\rm wd}}$.

$$\begin{cases} \frac{R_{\rm sdl}}{R_{\rm wdl}} > \frac{R_{\rm sd}}{R_{\rm wd}}, & \text{SD will be the donor,} \\ \frac{R_{\rm sdl}}{R_{\rm wdl}} = \frac{R_{\rm sd}}{R_{\rm wd}}, & \text{Two components will contact,} \\ \frac{R_{\rm sdl}}{R_{\rm wdl}} < \frac{R_{\rm sd}}{R_{\rm wd}}, & \text{WD will be the donor.} \end{cases} \tag{2}$$

$$\begin{cases} \frac{\partial \ln R_{\rm sd}}{\partial q} > \frac{\partial \ln R_{\rm sdl}}{\partial q}, & \text{SD is the donor and mass transfer is stable,} \\ \frac{\partial \ln R_{\rm wd}}{\partial q} > \frac{\partial \ln R_{\rm wdl}}{\partial q}, & \text{WD is the donor and mass transfer is stable.} \end{cases} \tag{3}$$

The $\lg q$-$M_{\rm tot}$ diagram is depicted according to Equations (2) and (3), and from this diagram, we are able to decide which evolutionary process a binary system will experience.

3 EVOLUTIONARY TRAJECTORY OF SD-WD SYSTEM IN LISA' S AMPLITUDE-FREQUENCY DIAGRAM

Based on the assumptions mentioned above, we derive the evolutionary trajectory of an SD-WD system in the amplitude-frequency diagram. When a system is in the in-spiral phase, it will evolve along the trajectory defined by the following equation

$$\lg rh_{\rm norm} = \frac{1}{3} \lg M_{\rm tot}^5 Q^3 + \frac{2}{3} \lg f, \tag{4}$$

where the total mass and mass ratio remain constant during this phase, r is the distance between the observers and the sources, and h is the amplitude of gravitational wave when it reaches the detector. Simply speaking, h is apparent brightness while rh is absolute luminosity. In the equation above, $Q = \frac{q^2}{1+q}$. Since we choose the Chandrasekhar mass as the mass unit and the solar radius as the length unit, the frequency unit here is 2.40×10^{-4} Hz, and the unit of $rh_{\rm norm}$ is 2.60×10^{-2} m. When the system enters the stable mass transfer phase, it evolves along the curve given by the following equations

$$\begin{cases} \lg rh_{\rm norm} = 2 \lg M_{\rm tot} + \lg Q - \lg \frac{f_2(q,\, M_{\rm tot})}{f_1(q)}, \\ \lg f = \frac{1}{2} \lg M_{\rm tot} - \frac{3}{2} \lg \frac{f_2(q,\, M_{\rm tot})}{f_1(q)}, \end{cases} \tag{5}$$

where the total mass is a constant because of the assumption that the total mass is conserved and mass ratio changes with time, $f_2(q,\ M_{\rm tot})$ is the mass-radius relationship for the donor, and

$$f_1(q) = \frac{0.49q^{\frac{2}{3}}}{0.6q^{\frac{2}{3}} + \ln(1+q^{\frac{1}{3}})}, \tag{6}$$

which is the ratio of the Roche lobe radius and separation between the two components (Kopparapu & Tohline 2007).

The change rate of frequency can be written in a compact form (Kopparapu & Tohline 2007)

$$\frac{{\rm d}f}{{\rm d}t} = \frac{3f}{\tau_{\rm chirp}}[2g(q,\ M_{\rm tot}) - 1], \tag{7}$$

where $\tau_{\rm chirp}$ is the time scale of inspiral phase,

$$g = \begin{cases} 0, & \text{inspiral phase,} \\ \frac{1-q}{\Delta\zeta}, & \text{stable mass transfer phase.} \end{cases} \tag{8}$$

We take two systems with the same total mass $M_{\rm tot} = 0.6M_{\rm ch}$ and $q = 3$, $q = \frac{1}{3}$ respectively as an example. The former one lies in Region I1 in Figure 2, so after the in-spiral phase, the white dwarf will act as a donor and the system will enter the stable mass transfer phase; the latter lies in Region II1, so the strange dwarf will be the donor and the system will also enter the stable mass transfer phase. Figure 3 shows how these two systems evolve across the $\lg f$-$\lg rh$ diagram.

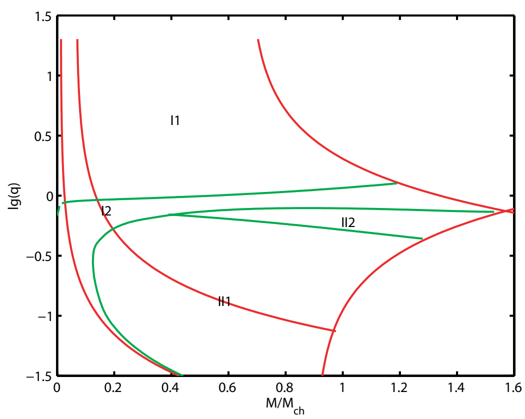

Fig. 2 $\lg q$-$M_{\rm tot}$ diagram. I1: white dwarf will be the donor and stable mass transfer will happen; I2: white dwarf will be the donor and unstable mass transfer will happen; II1: strange dwarf will act as donor and stable mass transfer will happen; II2 strange dwarf will act as donor and unstable mass transfer will happen. If a system is located in Region II1, the strange dwarf, which is the donor, will eventually lose all its ordinary mass crust, with a nearly naked strange matter core left, and be in contact with the accretor. A merger between the strange matter core and the white dwarf will happen, but this is beyond the scope of our investigation.

4 CONCLUSIONS

From the analysis in Section 3, we can see that once a binary system evolves into the mass-transfer phase, its location on LISA' s amplitude-frequency diagram largely depends on the physical properties of the donor, such as its mass-radius relationship. With the model mentioned in Section 1, we are able to determine the region where binaries possessing a particular kind of donor, such as strange dwarf and

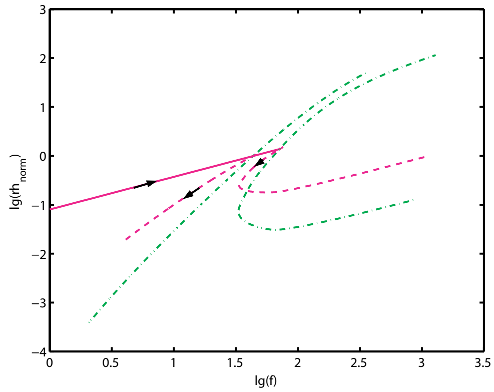

Fig. 3 Upper straight line is the trajectory of the in-spiral phase for both of the systems. The dash-dot curves are the termination boundaries of the in-spiral phase for systems with the same mass ratio; the left one is for $q = 3$, and the right one for $q = 1/3$. Once a system reaches its termination curve, it will change its direction and evolve along the dashed curve, which means it enters the stable mass transfer phase. From the diagram, it can be observed that if a system with a white dwarf as its donor enters the stable mass transfer phase, its frequency will get smaller and smaller, while a system with a strange dwarf as its donor has a minimum frequency value or a maximum period of about 1 min.

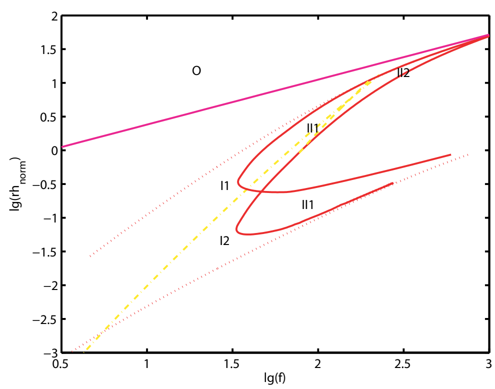

Fig. 4 Population boundaries for SD-WD binaries.

white dwarf, which are the ones mainly discussed in this paper, will be located. Therefore, by locating a source on the absolute magnitude-frequency diagram, it is possible to identify what kind of star the donor is. Figure 4 shows those regions in details.

Region O: no SD-WD systems will be located in this region. One of its boundaries, which is the upper straight line in the figure, is the evolutionary trajectory of the systems in the in-spiral phase and with the maximum possible mass. So, binaries with more massive components, such as neutron stars, are likely to exist in this region.

Region I: systems in the mass-transfer phase with a white dwarf as the donor are located in this region. The upper and the lower boundaries of this region, which are the two dotted lines in the figure, are defined by Equation (5), where the mass of the strange star equals its upper limit and the lower limit respectively. The right boundary is the left solid curve that corresponds to the line in Figure 2, which divides the whole region into part I and part II. The dot-dash line divides this region into two parts. I1 is the region where the mass transfer process is stable while I2 is the region where the process is unstable. So, most of the systems with white dwarfs as the donor should be located in Region I1. Since the evolutionary behavior during the stable mass transfer phase is largely determined by the physical properties of the donor, the counterpart of Region I1 for a double white dwarf population is quite similar.

Region II: systems with strange dwarfs as the donor exist in this region. The dashed curve divides this region into two parts. Region II1 is where the mass transfer process is stable.

If a system has mass larger than the Chandraskhar Mass or the upper limit mass of a strange dwarf, it is likely that the accretor will experience a violent explosion once its mass is beyond its own upper limit. For white dwarfs, the explosion is a type I supernova. Therefore, systems found in the upper parts of Region I1 or II1, which have large total masses, are progenitors of such violent phenomena.

From Figure 4, we can see that Region I1 and Region II1 overlap. If a gravitational wave source is located in the overlap, it is impossible to determine whether the donor is a white dwarf or a strange dwarf. However, if the source is located in the other part of Region I1 or the other part of Region II1, we are able to figure out what kind of star the donor is.

5 DISCUSSION

In this paper, we have only analyzed the possible observational characteristics of binary systems with strange dwarf or white dwarf components. A thorough analysis of all kinds of compact binary systems, such as a binary consisting of a neutron star and a white dwarf, is more meaningful. It can provide us with a new method to study objects and help settle many problems arising from inadequate information gained from electromagnetic signals.

The EOS of strange quark matter is still uncertain. Different values of the parameters in the EOS can result in different mass-radius relationships and therefore lead to different evolutionary behaviors in the amplitude-frequency diagram. So, analysis of and comparison between different strange dwarf models are necessary in order to verify the accuracy of those EOSs of strange matter.

The model we have used here to study the evolution of binary dwarf systems is greatly simplified. Actually, there are many other factors that may affect the evolutionary behaviors of compact binaries to some extent, even significantly. For example, if there is strong irradiation because of accretion, it can affect the thermal evolution of the donor. Therefore, the mass-radius relationship of a single isolated star is not accurate in this situation. This mechanism has been used to explain the unusually large size of the donors of several compact binaries (Bildsten & Chakrabarty 2001). The presence of tidal stress also affects the size and shape of both of the two components, and thereby the mass distribution of the system as a whole. In fact, the expression for gravitational radiation we use here is accurate only when the two components can be treated as two mass points. Moreover, if there is a strong stellar wind from the accretor, the assumption of conserved total mass will be false. In conclusion, it is necessary to conduct more accurate and detailed study of the evolution of the compact binary and its gravitational radiation.

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