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Double white dwarf mergers and type Ia supernovae

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We introduce our recent studies on the double-degenerate (DD) scenario, especially the Dynamically-Driven Double-Degenerate Double-Detonation (D^6) model. We have performed hydrodynamics simulations of the D^6 model. At the first step, we have reproduced the D^6 explosion, and found that its supernova ejecta has a non-spherical shape. At the second step, we have followed the supernova remnant evolution of the supernova ejecta, and found that the non-spherical shape survives during a few 10^3 years, and it will be detected by detail observations. We have also assessed if multi-messenger observations can identify the relation between double white dwarfs and some transients. We have found that Japanese space-borne gravitational-wave observatory DECIGO should play a dominant role fot that.

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1. Introduction

Type Ia supernovae (SNe Ia) have been recorded since ancient times because of their brightness and high occurrence rate. In the present day, SNe Ia are still important; they are used as a cosmic standard candle, and they should be a dominant source of iron group elements. There is broad consensus that SNe Ia are thermonuclear explosion of carbon-oxygen (CO) white dwarfs (WDs) in binary stars [1]. However, the stellar type of the WDs' companion stars remains unsettled. They can be non-degenerate stars (Single degenerate scenario: SD scenario) [2, 3], another WDs (Double degenerate scenario: DD scenario) [4, 5], or stellar cores of giant stars [6] (core degenerate scenario: CD scenario).

Observations of a nearby SNe Ia SN2011fe have put strong constraints on the nature of the companion star of SN2011fe. The companion star cannot be a red-giant star [7], helium star, nor main-sequence star [8]. This has ruled out most of the SD scenario. Moreover, hypervelocity WDs have been discovered with the help of Gaia mission [9, 10]. This strongly supports the Dynamically-Driven Double-Degenerate Double-Detonation (D^6) model. Note that such hypervelocity WDs are are by-products of D^6 model, one of the DD scenario.

As described above, the DD scenario, especially D^6 model, have rapidly attracted attention as a promising SN Ia progenitor model. Here, we introduce our three studies related to the DD scenario, especially the D^6 model. First, we show our hydrodynamics simulations to reproduce the D^6 model. Second, we present our study to examine supernova remnant (SNR) phases of the D^6 model, based on the first study. Finally, we suggest multi-messenger astronomy for the DD scenario.

2. Explosion simulations of the D^6 model

We have performed the explosion simulations of the D^6 model by means of smoothed particle hydrodynamics (SPH) simulation coupled with nuclear reaction networks. The SPH code is parallelized by FDPS numerical library [11], and vectorized by SIMD technique [12, 13]. The SPH code is equipped with the Helmholtz equation of state [14] and the Aprox 13 reaction networks [15]. As an initial condition, we prepare a double WD system: $1.0M_\odot$ CO WD with $0.05M_\odot$ helium outer shell as a primary WD and $0.6M_\odot$ CO WD as a secondary WD. We put a hot spot in the helium outer shell to start helium detonation artificially. Then, the primary WD successfully achieves double detonation explosion.

We have investigated the supernova ejecta properties [16] (see also [17]). The chemical components are typical of SNe Ia: $0.55M_\odot$ ^{56}Ni, $0.15M_\odot$ Si, and $0.07M_\odot$ O. On the other hand, the ejecta has a non-spherical shape because of the presence of the secondary WD. This is called "ejecta shadow". The ejecta shadow will survive the SNR phase, and could be evidence of the D^6 model (see the next section). The chemical element distribution also has asymmetry. The supernova ejecta strips surface materials of the secondary WD. It shapes a stream-like CO structure. Since the CO component stays at the central region of the supernova ejecta, it could be seen in the nebular phase of the D^6 model.

Additionally, we show several WD explosion simulations [18]. Among them, both of two WDs explode, and the supernova ejecta contains $\sim 1M_\odot$ ^{56}Ni, and has non-spherical shapes more significantly than the above simulations. However, in these simulations, the separation of the two

WDs is unrealistically close, and the helium outer shell mass is unrealistically massive. Such explosions might be unfeasible in reality.

3. SNR simulation of the D^6 model

The ejecta shadow of the D^6 supernova ejecta motivates us to examine if it survives during its SNR phase. We have performed a hydrodynamics simulation based on the WD explosion simulation in Tanikawa et al. (2018) [16] to investigate the SNR evolution during more than 10^4 years [19].

The ejecta shadow survives during a few 10^3 years. The ejecta shadow has smaller number density than the other region, and thus the reverse shock of the SNR proceeds more rapidly. Consequently, the SNR does not have a spherical shape. This shape is prominent, in particular before the reverse shock reaches the center of the SNR. This SNR property can be made use of to identify the SNR of the D^6 explosion.

4. Multi-messenger astronomy for the DD scenario

Japanese space-borne gravitational-wave (GW) observatory DECIGO [20] has high sensitivity at the GW frequency of 0.1 Hz. This means that DECIGO can observe a double WD just before one of the two WD is tidally disrupted, and the two WDs merge. Assets of DECIGO are its accuracy for WD mass estimate ($\lesssim$ 10 %), sky localization ($\lesssim$ 0.1 deg^2), and time resolution ($\lesssim$ 1 second) for a double WD merger at the redshift of 0.08 within which several 10^3 SNe Ia happen during one year.

We have found that multi-messenger astronomy should be a powerful tool to identify the SN Ia progenitors [21]. DECIGO can detect the dissapearance of GWs from a double WD. If some transient can be observed by electromagnetic telescopes a few days later at the same place, the double WD should be the progenitor of the transient. DECIGO can determine the masses of the two WDs, and electromagnetic telescopes can determine the transient type. Currently, there are various types of transients suspected of involvement by WD explosions [22]. Such multi-messenger observations will resolve the relation between double WDs and these transients.

5. Summary

We summarize our recent studies related to the DD scenario and the D^6 model. We have investigated the D^6 model from its explosion phase to the SNR phase [16, 18, 19]. Its SNR has an unique shape. Detail observations of SN Ia SNRs should reveal if SN Ia SNRs are generated from the D^6 model or not. When combined with electromagnetic telescopes, Japanese space-borne GW observatory DECIGO should be powerful to identify the relation between double WDs and transients related to WD explosions [21].

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