Numerical Study of Thermonuclear Explosion of White Dwarfs Induced by Tidal Disruption Events

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It is important to find intermediate mass black holes (IMBHs) by measuring black hole mass, since a few IMBHs have been observed so far. Tidal disruption events (TDEs) of white dwarfs (WDs) by IMBHs can be a clue to search for IMBHs. WD TDEs illuminate only IMBHs, since WDs are just swallowed by massive black holes. We have studied WD TDEs by numerical simulation, and have shown detonation emerges in the middle of WD TDEs, which is so-called "tidal detonation". The tidal detonation yields large amounts of radioactive nuclei, such as Nickel-56. WD TDEs will have radioactive luminosity powered by these nuclei, similarly to type Ia supernovae. We will present observational features of WD TDEs.

Keywords: black hole physics; hydrodynamics; nuclear reactions, nucleosynthesis, abundances; supernovae: general; white dwarfs.

1. Introduction

In a tidal disruption event (TDE), a star is tidally disrupted by a black hole (BH). A main-sequence star can be disrupted by BHs with $\lesssim 10^8 M_\odot$. On the other hand, a white dwarf (WD) is swallowed by BHs with $\gtrsim 10^5 M_\odot$ rather than disrupted. Hence, a WD TDE can be a powerful tool to search for intermediate mass BHs (IMBHs) with 10^2 - $10^5 M_\odot$. Note that a few IMBHs have been discovered so far.

A WD TDE is theoretically predicted to experience thermonuclear explosion in the following reason. When a WD approaches to an IMBH, it is extended in the direction of the orbital plane (hereafter, x-y plane), however it is compressed in the direction normal to the orbital plane (hereafter, z-direction). The compression heats the WD materials, triggers explosive nuclear reactions, and explode the WD.

It has been reported in Ref. 1 that smooth particle hydrodynamics (SPH) simulation demonstrates thermonuclear explosion of a WD in a TDE, triggered by shock compression. However, it has been shown in Ref. 2 that their SPH simulation suffers from low space (or mass) resolution, and raises spurious heating. Eventually, the spurious heating triggers WD explosion in SPH simulation in Ref. 1.

In this paper and Refs. 3, 4, we assess whether a WD experiences thermonuclear explosion in a TDE, or not. Ultimately, we show a WD can explode. So, we also present nucleosynthesis of a WD. This paper is structured as follows. In section 2, we describe our numerical method. In section 3, we show our numerical results. In section 4, we summarize this paper.

2. Method

We have to perform hydrodynamics simulation with extremely high space resolution, in order to assess whether a WD experiences thermonuclear explosion in a WD TDE. For the extremely high space resolution, we combine 1 dimensional (1D) simulation with 3 dimensional (3D) simulation. We first follow overall WD TDE by 3D SPH simulation. Next, we extract columns of the WD along the z-direction, hereafter z-columns. We follow hydrodynamic evolution of the z-columns by 1D mesh simulation.

In our 3D SPH simulation , we adopt the Helmholtz equation of state (EoS) without Coulomb corrections in Ref 5. We do not consider nuclear reactions. Our initial condition in the 3D SPH simulation is as follows. A WD has $0.45 M_\odot$ with pure He component. The number of SPH particles per a WD is 300 millions. The IMBH mass is $300 M_\odot$. We model the IMBH gravity as newton gravity. The WD orbit is parabolic, and its penetration factor is $\beta = 7$, where the penetration factor is the ratio of tidal disruption radius to pericenter distance.

We extract nine z-columns from the 3D SPH simulation. We use the z-columns as initial conditions of 1D mesh simulation. The method of the 1D mesh simulation is as follows. We use the FLASH code in Ref. 6. We also adopt the Helmholtz (EoS) without Coulomb correction. Moreover, we use Aprox13 for nuclear reaction networks in Ref 7. We confirm that z-column evolution in 1D mesh simulation is the same as in 3D SPH simulation, if we do not include nuclear reaction networks in 1D mesh simulation.

3. Results

Figure 1 shows density of a WD in a TDE, and position of an extracted z-column. This is the results of 3D SPH simulation. In the z-column, WD materials are being compressed, and are bouncing soon.

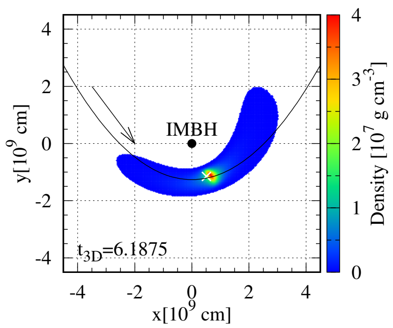

Fig. 1. Density of a WD, and position of a z-column. The black curve indicates the WD orbit, and the black arrow points to the orbital direction of the WD.

Figure 2 shows time evolution of the z-column shown in Figure 1. At $t = 0.0264$ s, the z-column bounces back, and generates a pressure wave. The pressure wave steepens into a shock wave just after $t = 0.0391$ s. The shock wave triggers explosive nuclear reactions, and the nuclear reactions generate a detonation wave. The detonation wave propagates backward, and burns out the z-column overall. The detonation wave yields 80 % of ^{56}Ni, and leaves 20 % of ^{4}He. This is because the burned materials have high density, $\gtrsim 10^6$ g cm^{-3}.

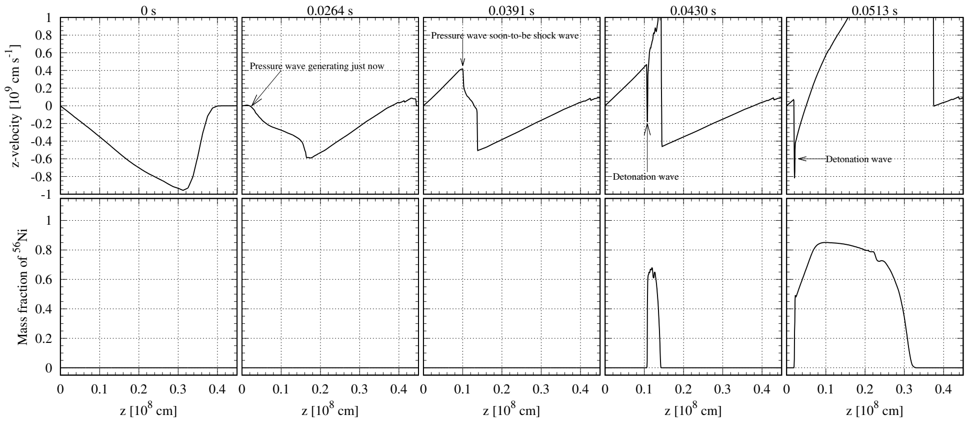

Fig. 2. Time evolution of the z-column shown in Figure 1. The top and bottom panels show z-velocity and mass fraction of ^{56}Ni, respectively.

4. Summary

We numerically show a WD can experience thermonuclear explosion in a TDE. Although we present the results of one z-column, detonation waves are generated in 7 of 9 columns. From these results, we estimate this WD TDE yields $0.3M_\odot$ of ^{56}Ni. Hence, this WD TDE should be as bright as normal type Ia supernovae (SNe Ia). However, its luminosity would change more rapidly than SN Ia's one, since the WD has smaller photon's diffusion timescale than those of SNe Ia in two respects. First, a disrupted WD would have smaller mass than WDs of SNe Ia. Second, a disrupted WD is distorted by the tidal field of the IMBH. Therefore, we can distinguish WD TDEs from SNe Ia.

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