

論文の内容の要旨

Observational signatures from tidal disruption events of white dwarfs

(白色矮星の潮汐破壊現象からの観測兆候)

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Recent advances in optical surveys have yielded a large sample of astronomical transients, including classically known novae and supernovae (SNe) and also newly discovered classes of transients. Among them, tidal disruption events (TDEs) have a unique feature that they can probe massive black holes (MBHs). A TDE is an event where a star approaching close to a BH is disrupted by tides of the BH (see Figure 1). The disrupted star leaves debris bound to the BH emitting multi-wavelength and multi-messenger signals, which are observed as a transient. The observational signatures of TDEs bring us insights into physical processes around the BH, such as dynamics in the general relativistic gravity, accretion physics, and environmental information around BHs. Event rates of TDEs also inform us of populations of BHs.

A large number of BHs have been detected, but still there are big mysteries. The most mysterious BHs are intermediate mass BHs (IMBHs) because they are a missing link: there is almost no certain evidence of IMBHs, while there are many detections of stellar mass BHs and supermassive BHs (SMBHs). Searches for IMBHs are not only important to reveal mysteries of IMBHs themselves, but also to understand origin(s) of SMBHs. Several scenarios to form SMBHs have been proposed, but it is still unclear which scenario(s) are real in the Universe. A distinguishable point is a mass distribution of IMBHs because the different scenarios would result in different mass distributions. Thus, finding IMBHs would play a crucial role to understand nature of massive BHs.

In this thesis, we study TDEs where a white dwarf (WD) is disrupted by an IMBH to probe IMBHs. This is motivated by the nature of WD TDEs that an SMBH cannot tidally disrupt a WD because the SMBH swallows the WD before the disruption, and thus there is no observable except for gravitational waves. Detection of WD TDEs implies that of the disrupting IMBH, and thus WD TDEs are good probes of IMBHs. WD TDEs have another interesting feature: a WD possibly ignites thermonuclear explosions by tidal compression if the WD-BH encounter is close enough. Once the thermonuclear explosions occur, radioactive nuclei such as ^{56}Ni are

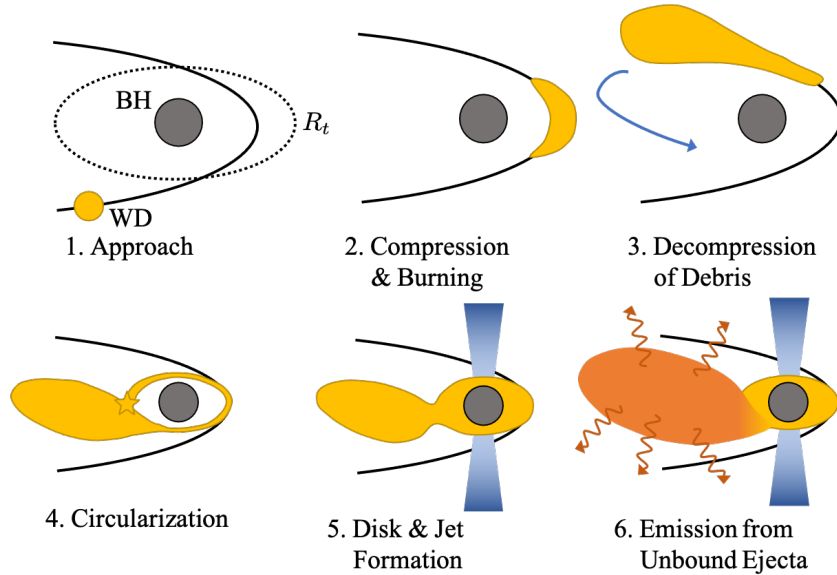


Figure 1 Sequence of events in a WD TDE. The WD approaches the BH with the parabolic orbit with its pericenter radius smaller than the tidal radius R_t . The tidal compression perpendicular to the orbital plane can ignite explosive thermonuclear reactions within the WD. Bound debris of the WD falls back on to the BH and forms an accretion disk and possibly relativistic jets later. The unbound debris emits optical radiation powered by decays of radioactive nuclei synthesized in the thermonuclear explosions.

synthesized. Then debris of the WD unbound to the IMBH possibly cause emission powered by decays of the radioactive nuclei. It is naively expected that the emission could be similar to that of SNe Ia because of the similarity in the thermonuclear explosions of a WD.

With these motivations, efforts to find WD TDEs have been dedicated. Although a few possible candidates of WD TDEs have been reported, they are not confirmed as WD TDEs and other origins are also proposed. Event rates of WD TDEs are also uncertain because of the unknown nature of IMBHs, but it is still expected that the current or upcoming optical surveys possibly detect WD TDEs. To search for WD TDEs among transients found by those surveys, it is needed to model the observational signatures from WD TDEs in more detail. Especially, a variety of emission from thermonuclear explosions in WD TDEs are unknown, and thus it is difficult to point out distinguishable features of WD TDEs with other transients.

This thesis aims to reveal the variety and characteristics of observational signatures from thermonuclear explosions in WD TDEs, and to constrain properties of IMBHs. To this end, we perform a suite of three different numerical simulations considering 5 parameter sets of WD TDEs. We take the WD mass as the main parameter to be varied over 0.2, 0.4, 0.6, 1.0, and 1.2 solar mass (M_\odot). First, we perform three-dimensional hydrodynamic simulations coupled with simplified nuclear reaction networks, and follow dynamical evolution of the tidal disruption of a WD by a BH and thermonuclear explosions in the disruption phase. Second, we perform detailed nucleosynthesis simulations in a post-process manner, and derive the synthesized nuclear compositions of the unbound ejecta. Finally, we perform radiative transfer simulations, and follow generation of photons by the radioactive decays, interactions of the photons with the unbound ejecta, and escapes of the photons from the ejecta, from which we derive the synthetic observational signatures.

We derive multi-band light curves and spectral evolutions of the 5 models as templates of the thermonuclear emission from the WD TDEs (see Figure 2). On photometric properties,

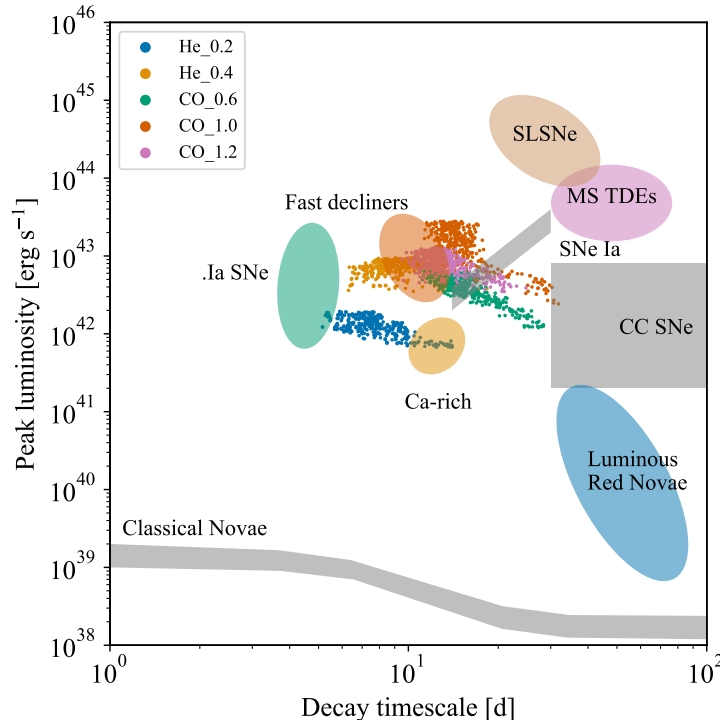


Figure 2 Decay timescale and peak luminosities of observed transients and our WD TDE models. The areas filled with the colors show some classes of observed transients. The points show our models, where we consider various viewing angles for each model. The abbreviations are as follows: core-collapse supernovae (CC SNe), type Ia supernovae (SNe Ia), superluminous supernovae (SLSNe), main sequence tidal disruption events (MS TDEs), .Ia supernovae (.Ia SNe), and calcium-rich transients (Ca-rich). The $0.2 M_{\odot}$ model exceptionally shows rapid and faint light curves, while the other models show the similar photometric properties to SNe Ia.

the $0.2 M_{\odot}$ model exceptionally shows relatively faint ($L_{\text{peak}} \sim 10^{42} \text{ erg s}^{-1}$) and rapidly evolving light curves (decay timescale $\simeq 5\text{--}10$ d), because the ejecta mass and ^{56}Ni mass are low ($0.12 M_{\odot}$ and $0.03 M_{\odot}$, respectively). The 0.4 , 0.6 , 1.0 , and $1.2 M_{\odot}$ models are similar to some classes of thermonuclear transients, or SNe Ia, in photometric properties such as the bolometric peak luminosity, decay timescale, B -band peak magnitudes, and B -band decay timescale. However, they commonly show higher temperature than the observed thermonuclear transients around their B -band peaks. The difference can be used as a signature to distinguish the thermonuclear emission from WD TDEs from the other thermonuclear transients. All the models show a large variety in their light curves dependent on viewing angles because the ejecta is very aspherical due to the tidal disruption.

On spectroscopic properties, our WD TDE models are indeed similar to observed thermonuclear transients in some senses, such as absence of hydrogen lines and appearance of lines of iron group elements and calcium. However, there is a difference in lines of intermediate mass elements (IMEs): the observed thermonuclear transients show strong IME lines, while our models show (very) weak IME lines because of the nucleosynthesis yielding low mass IMEs. This difference might not be conclusive because the synthesized IME masses are sensitive to numerical resolutions, and simulations with higher resolutions might result in larger IME masses and thus in stronger IME lines. Another more robust difference is Doppler shifts of spectra shown in our models. The Doppler shifts are caused by the bulk motion of unbound ejecta escaping from the BH with velocities of $\gtrsim 10^4 \text{ km s}^{-1}$. Although the Doppler shifts depend on

viewing angles, they can be a crucial signature to distinguish WD TDEs from other transients.

We search for observational counterparts of WD TDEs that show similar observational signatures to our models. For the 0.4, 0.6, 1.0, and 1.2 M_{\odot} models, we cannot find any good match in multi-band light curves between our models and observed transients. For the 0.2 M_{\odot} model, we find two observational candidates in relatively faint and rapid transients, which show similar multi-band light curves to the model. Because their spectra are not observed, we cannot confirm their origin as a WD TDE by comparing the spectra. However, one of the transients has a distant 10.2 kpc offset from the center of its host galaxy. This may support interpreting its origin as a WD TDE, of which a star cluster containing an IMBH and WD is the plausible environment.

The photometric properties of our models cover a wide phase space. There could be a more variety of them because the intrinsic parameter sets of WD TDEs (M_{WD} , M_{BH} , β) can vary over a wider parameter space than the 5 parameter sets. We discuss the possible range of the variety of observational signatures of WD TDEs by applying the so-called Arnett rule. First, we check the validity of the application of the Arnett rule by comparing the peak time and peak luminosity predicted by the Arnett rule and by our numerical simulations. They show reasonable matches, and thus we next apply the Arnett rule to results of hydrodynamic simulations of WD TDEs considering 180 parameter sets. The results show that there could be more slowly evolving and much fainter WD TDEs ($L_{\text{peak}} \gtrsim 10^{38} \text{ erg s}^{-1}$) than our 5 models ($L_{\text{peak}} \sim 10^{42} - 10^{43} \text{ erg s}^{-1}$), which arise from WD TDEs with weaker thermonuclear explosions. Such faint transients should also be searched for as WD TDEs.

Emission from WD TDEs is not only caused by thermonuclear explosions, but also by debris falling back on to the BH. If the luminosity of the fallback emission follows the mass fallback rate of the debris, the thermonuclear emission would be fainter than it. However, it is naively expected that the fallback luminosity is limited by the Eddington luminosity unless relativistic jets are viewed on-axis. Additionally, the accretion disk formed by the fallback debris would be bright mainly in X-rays. Thus, we expect that the thermonuclear optical emission is not significantly affected by the fallback emission in most cases.

If the two observational candidates are really WD TDEs, they inform us of the event rate of WD TDEs and the IMBH number density. The sum of their volumetric event rates are estimated as $\simeq 600 \text{ Gpc}^{-3} \text{ yr}^{-1}$. Considering a ratio of WD TDEs with thermonuclear explosions to all the WD TDEs, we obtain the total WD TDE rate as $\sim 3 \times 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$. Taking a WD TDE rate per an IMBH as that in centers of dwarf galaxies, we estimate the number density of IMBHs from the total WD TDE rate as $n_{\text{IMBH}} \sim 3 \text{ Mpc}^{-3}$. Although the confidence is not very high, this estimate is valuable because there has been almost no constraint on the number density of IMBHs.

The observational signatures of WD TDEs derived in this thesis are useful to search for WD TDEs with current and upcoming optical surveys. As we find two observed candidates of WD TDEs in the current transient sample, we would be able to find more WD TDE candidates with a much larger transient sample given by those surveys. There might be also WD TDEs detected with high certainties, showing good matches both in photometric and spectroscopic properties to our models. Such findings of WD TDEs would contribute to explore origins of observed transients, to study extreme physical processes around BHs, and to reveal unknown nature of massive BHs.