Properties of Thorne-Żytkow object explosions

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ABSTRACT

Thorne-Żytkow objects are stars that have a neutron star core with an extended hydrogen-rich envelope. Massive Thorne-Żytkow objects are proposed to explode when the nuclear reactions sustaining their structure are terminated by the exhaustion of the seed elements. In this paper, we investigate the observational properties of the possible Thorne-Żytkow object explosions. We find that Thorne-Żytkow object explosions are observed as long-duration transients lasting for several years. If the accretion disk triggering the explosions does not last for a long time, Thorne-Żytkow object explosions have a luminosity plateau with about $10^{39}$ erg s⁻¹ lasting for a few years, and then they suddenly become faint. They would be observed as vanished stars after a bright phase lasting for a few years. If the accretion disk is sustained for long time, the Thorne-Żytkow object explosions become as bright as supernovae. They would be observed as supernovae with rise times of several hundred days. We found that their photospheric velocities are 2000 km s⁻¹ at most, much smaller than those found in supernovae. Supernovae with extremely long rise times such as HSC16aayt and SN 2008iy may be related to the explosions of Thorne-Żytkow objects.

Key words: accretion, accretion discs – stars: neutron – stars: peculiar – supernovae: general – supergiants

1 INTRODUCTION

Thorne-Żytkow objects (TZOs) are hypothetical stars that have a neutron star core with an extended hydrogen-rich envelope (Thorne & Zytkow 1975, 1977). Such stars can be formed through the spiral-in of a neutron star into a companion star following unstable mass transfer (Taam et al. 1978), a supernova (SN) kick (Leonard et al. 1994) or an unsuccessful SN explosion (Utrobin & Chugai 2008).

Recent observations start to identify TZO candidates. Levesque et al. (2014) identified a chemical anomaly in a supergiant star HV2112 in Small Magellanic Cloud (Worley et al. 2016; McMillan & Church 2018) which is consistent with a TZO (Tout et al. 2014). It is also suggested that HV2112 may be an asymptotic-giant-branch star rather than a TZO (Tout et al. 2014; Beasor et al. 2018; O’Grady et al. 2020). There are ongoing observational efforts to discover TZOs (DeMarchi et al. 2021).

Massive (more than about 16 M⊙) TZOs, which are supported by the nuclear reactions near the neutron star surface (Cannon 1993; Biehle 1991), are expected to collapse when they burn all the seed elements required for the nuclear reactions (Bisnovatyi-Kogan & Lamzin 1984; Podsiadlowski et al. 1995). Moriya (2018) suggested that massive TZO collapses may lead to their explosion. In this study, we investigate the outcomes of the potential TZO explosions and show their expected observational properties.

The rest of this paper is organized as follows. First, we show our assumptions and methods to investigate the TZO explosion properties in Section 2. Then we present the expected TZO explosion properties in Section 3. We discuss the observational properties and possible TZO explosion candidates in Section 4. We summarize this paper in Section 5.

2 METHODS

In this section, we briefly introduce our TZO explosion model and our method to estimate the properties of TZO explosions.

2.1 Progenitor and explosion trigger

We take the 16 M⊙ TZO model of Biehle (1991) as we did in our previous study (Moriya 2018). Assuming a typical TZO angular velocity, Moriya (2018) showed that the accretion disk around the central neutron star is expected to appear at around 1 day after the onset of collapse when $10^{-3}$ M⊙ is accreted. The subsequent accretion time-scale becomes about 10 times longer than the free-fall time-scale, if we assume a typical viscosity parameter of 0.1. The estimated accretion rate $M_{acc}$ after 1 d since the onset of the collapse is presented in Fig. 1.

Once the accretion disk is formed, a fraction (η) of accreted energy could be released at the central region of the collapsing TZO through
Figure 1. Accretion rate $\dot{M}_{\text{acc}}$ towards the central compact object after accretion disk formation that is estimated to occur at around 1 day after the onset of the TZO collapse. The time $t$ is after the onset of the TZO collapse.

Figure 2. Mass accreted on to the central compact object after accretion disk formation. The time $t$ is after the onset of the TZO collapse. The right axis shows the injected energy to the collapsing TZO envelope through the accretion with an efficiency $\eta = 10^{-3}$. The dashed line shows the binding energy ($5 \times 10^{47}$ erg) of the TZO modelled.

an accretion disk wind or jet. When the energy sufficient to unbind the TZO has been released an explosion of TZO can be triggered. The energy input rate $\dot{E}_{\text{in}}$ at the centre is expressed as

$$\dot{E}_{\text{in}} = \eta M_{\text{acc}} c^2,$$

where $c$ is the speed of light. We adopt an efficiency $\eta = 10^{-3}$ in this study (e.g., Dexter & Kasen 2013). Fig. 2 shows the total accreted mass $M_{\text{acc}}$ after the disk formation at 1 day after the collapse and the total injected energy $\eta M_{\text{acc}} c^2$. In this work, we mainly consider the cases where the central energy injection occurs at wide angles, not in collimated jets.

Once the energy injection from the accretion disk has released more energy than the binding energy of the TZO, the TZO can explode. However, the accretion energy injection could be terminated by the outflows that push back the accreting materials. It is not clear when the accretion is terminated and so we introduce another parameter, $t_{\text{acc}}$, the time for which the accretion continues. Because the binding energy of the 16 M$_{\odot}$ TZO is $5 \times 10^{47}$ erg, the accretion needs to last at least for about 5 days to cause the TZO to explode (Fig. 2). The TZO explosion energy depends on $t_{\text{acc}}$. For $t_{\text{acc}} = 10$, 100 and 1000 d the explosion energies are $1.1 \times 10^{46}$ erg, $3.5 \times 10^{49}$ erg and $3.3 \times 10^{51}$ erg, respectively.

2.2 Radiation hydrodynamics calculations

In order to estimate the observational properties of TZO explosions, we use the one-dimensional multi-frequency radiation hydrodynamics code STELLA. We refer to Blinnikov et al. (1998, 2000, 2006) for the full details of the code. Briefly, STELLA calculates time-dependent equations of hydrodynamics and the angular moments of intensity averaged over a frequency bin with the variable Eddington method (Mihalas & Mihalas 1984). Spectral energy distributions (SEDs) are numerically evaluated at every time-step. When we define a photosphere, we take the location where the Rosseland-mean optical depth becomes 2/3. In this work, we put thermal energy with the rate of Eq. 1 at 1 M$_{\odot}$ from the centre. This is the surface of the central neutron star supporting the TZO. The energy injection begins 1 day after the onset of the collapse and continues until $t_{\text{acc}}$. Though we use a one-dimensional code to investigate the TZO explosion properties, the energy injection from the accretion disk is not necessarily spherically symmetric. The TZO explosion properties that we show here are applicable when the energy injection occurs on a large angular scale. Our models are not applicable if the energy injection occurs on a small angular scale through such as in collimated jets.

3 RESULTS

Fig. 3 shows the bolometric light curves of the TZO explosions with $t_{\text{acc}} = 10$, 100 and 1000 d. Their photospheric temperature and velocity are presented in Fig. 4. The synthetic $g$, $r$ and $i$ band light curves are presented in Fig. 5. Before the forward shock reaches the surface of the progenitor, the bolometric luminosity stays at the TZO luminosity of around $5 \times 10^{38}$ erg s$^{-1}$. The forward shock reaches the surface at 105 d ($t_{\text{acc}} = 10$ d) and 51 d ($t_{\text{acc}} = 100$ and 1000 d). The models with $t_{\text{acc}} = 100$ and 1000 d have the same shock-appearance date because the energy deposition is the same in the two models at the beginning.

The explosion with $t_{\text{acc}} = 10$ d is observed as a Type IIP SN-like transient with a very long plateau duration (Figs 3 and 5), as analytically predicted by Moriya (2018). The plateau duration is about 500 d and its bolometric luminosity is around $6 \times 10^{39}$ erg s$^{-1}$, although the luminosity continues to increase slowly until the end of the plateau. The absolute magnitudes in the $g$, $r$ and $i$ bands are around $-7.8$, $-9.5$, and $-10.3$, respectively, but they slightly depend on time. The photospheric velocity is relatively small (50 to 70 km s$^{-1}$, Fig. 4). The plateau phase is caused by the hydrogen recombination as in the case of Type IIP SNe. Once the recombination wave reaches the bottom of the envelope the plateau phase ends and the luminosity drops.

The explosion model with $t_{\text{acc}} = 100$ d has a light curve with a steady luminosity increase from around 150 d (Figs. 3 and 5). The bolometric luminosity reaches a peak at 400 d with $3 \times 10^{41}$ erg s$^{-1}$. The luminosity is sustained even after the termination of the energy injection at 100 d because of the hydrogen recombination as in the case of Type IIP SNe. In this model, the recession of the recombination wave in the Lagrangian frame is slower than the ejecta expansion in the Eulerian frame. Thus, the luminosity increases as the recombination wave recedes towards the centre of the expanding envelope.

The time of the luminosity peak corresponds to the moment when the expansion wave reaches at the bottom of the ejecta. Right after
that the luminosity suddenly declines. The photospheric velocity is around 500 km s\(^{-1}\) (Fig. 4).

When the accretion energy input is sustained for 1000 d (\(t_{\text{acc}} = 1000\) d), the luminosity increases for 1000 d as seen in Figs 3 and 5. The luminosity peak is reached at 1000 d when the energy injection is terminated. The peak bolometric luminosity is \(8 \times 10^{43}\) erg s\(^{-1}\). We find the peak optical magnitudes are around \(-20.7\). The long-lasting luminosity source is the steady accretion towards the centre. The photospheric velocity is 1000 to 2000 km s\(^{-1}\) (Fig. 4).

4 DISCUSSION

In the previous section, we have found that TZO outbursts should be observed as long-lasting transients with durations of more than 100 d. The expected luminosity range is diverse, ranging from those that are similar to massive stars (about \(10^{39}\) erg s\(^{-1}\)) to SNe (about \(10^{43}\) erg s\(^{-1}\)). The faintest TZO explosions with \(t_{\text{acc}} = 10\) d are difficult to discover because of their subtle luminosity change as well as their faintness. They could be discovered as vanishing stars after a short luminosity increase lasting for a few years. Such an event could be discovered during a survey for disappearing stars (Kochanek et al. 2008; Adams et al. 2017b,a; Neustadt et al. 2021).

If the energy input from the accretion is sustained long enough, the TZO explosions become as bright as SNe and we expect to find them among SN candidates. We predict that TZO explosions have much longer time-scales (more than 100 d) than typical SNe (less than 100 d). Thus, TZO explosions can be discovered among unusually long-lasting SNe. In Fig. 6, we compare our TZO light curve models with some long-lasting SNe, HSC16aayt (Moriya et al. 2019) and SN 2008iy (Miller et al. 2010) are Type IIb SNe showing narrow emission lines that are interpreted to originate from the interaction between dense circumstellar media and SN ejecta. The photospheric velocities of the TZO explosions are predicted to be lower than those of SNe and so relatively narrow spectral features may actually originate from small photospheric velocities. It is also possible that the extended TZO progenitors experience mass loss that leads to the narrow spectral features. The long-lasting SNe with the rise times of more than 100 d are promising candidates for TZO explosions.

Another well-known mysterious long-lasting SN with an extremely long duration is iPTF14hls (Arcavi et al. 2017; Sollerman et al. 2019). Its origin is still not clear (e.g., Woosley 2018; Moriya et al. 2020). While the duration is consistent with our TZO explosion models, iPTF14hls has a photospheric velocity of 4000 km s\(^{-1}\) which is much higher than what we predict for our TZO explosions. In addition, we do not expect to have the bumpy light curves as found for iPTF14hls (Fig. 6). Thus, iPTF14hls is not likely related to a TZO explosion.

With an estimated Galactic TZO birth rate of about \(10^{-4}\) yr\(^{-1}\) (Podsiadlowski et al. 1995; Ablimit et al. 2021) and a Galactic SN rate of about \(10^{-2}\) yr\(^{-1}\) (Li et al. 2011), about 1% of SNe may come from TZO explosions\(^1\). SNe lasting for more than 100 d are rare and their event rates are not likely as high as 1% of SNe. This may mean that most TZO explosions are faint and difficult to discover. If the energy injection from the accretion disk is not usually sustained for a long time, most TZO explosions would be observed only as faint transients. Thus, searching for disappearing stars that accompany faint transients is more likely a promising way to discover exploding TZO. Other possibilities are that the TZO birth rate is lower than \(10^{-4}\) yr\(^{-1}\) or TZO do not explode at all.

Distinguishing TZO explosions from similar explosions that are triggered by iron core collapse is quite challenging. Although core collapse of massive stars around 16 M\(_{\odot}\) usually ends up with successful SN explosions, it is possible that some of them fail to explode

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\(^1\) We note that the event rate estimate of Moriya (2018) has typos.
Figure 5. Synthetic light curves of the TŻO explosions in the $g$, $r$, and $i$ bands. The time $t$ is after the onset of the TŻO collapse.

Figure 6. Comparison of synthetic TŻO light curves having $t_{acc} = 500$ and 700 d with long-lasting SNe, HSC16aayt (Moriya et al. 2019), SN 2008iy (Miller et al. 2010), and iPTF14hls (Arcavi et al. 2017; Sollerman et al. 2019). Time is arbitrary shifted to match the observations and models.

5 SUMMARY

We here investigated the observational properties of TŻO explosions. We found that TŻO explosions lead to transients with the durations of 100 to 1000 d. The possible luminosity range is quite diverse $10^{39}$ to $10^{44}$ erg s$^{-1}$. This depends on the duration of the energy input from the accretion disk triggering the TŻO explosions. The faintest TŻO explosions, which appear when the accretion energy injection is not sustained for long, have similar luminosities to those of massive stars. As in the case of Type IIP SNe, the light curves are expected to have a long plateau phase. The plateau phase of TŻO explosions lasts for a few years. Their photospheric velocity is 50 to 70 km s$^{-1}$. They may be observed as vanishing stars after brightening for several years. The bright TŻO explosions, which appear when the accretion energy injection lasts a long time, can be observed as SNe with rise times of several hundred days. We found that the expected light curves are similar to those of some long-lasting SNe such as HSC16aayt and SN 2008iy, although they are Type IIn SNe. The photospheric velocity is expected to be of the order of 100 km s$^{-1}$.

While we only have a few SNe that have long-duration light curves similar to our synthetic light curves from TŻO explosions, many long-duration SNe will be found in the coming era of the Rubin Observatory’s Legacy Survey of Space and Time (LSST). Since the faintest TŻO explosions are expected to have luminosities that are similar to massive stars, they can be eventually found as disappeared stars.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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