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Thorne- ˙Zytkow Objects: Observational and Research Advances (Postprint)

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Abstract

Recently, gravitational wave detections have revealed numerous unexpected binary merger events, evidently indicating that our understanding of binary evolution—this most fundamental problem in astrophysics—remains significantly deficient. Efforts to remedy this deficiency cannot be limited solely to relying on such rare transient events as binary mergers; we must simultaneously seek other independent clues and phenomena that are more suitable for long-term observations. Thorne- ˙Zytkow Objects (abbreviated as T ˙ZO), as hypothetical exotic celestial objects with a degenerate neutron core embedded within a red giant or red supergiant, represent an excellent research subject for understanding binary evolution. First, we provide a comprehensive theoretical overview of the structure and evolution of massive T ˙ZOs; then, we primarily introduce the relevant observational discoveries of massive T ˙ZOs, particularly HV2112 in the Small Magellanic Cloud; finally, we provide a summary and outlook on current related work.

Full Text

Preamble

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The Observation and Research Progress on Thorne-Żytkow Objects

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Abstract

Recent gravitational wave detections have revealed numerous unexpected binary merger events, clearly demonstrating that our understanding of binary evolution—one of the most fundamental problems in astrophysics—remains significantly incomplete. Efforts to address this deficiency cannot rely solely on rare transient events such as binary mergers; we must simultaneously seek other independent phenomena more suitable for long-term observation. Thorne-Żytkow Objects (TZOs), hypothetical celestial bodies formed when a degenerate neutron star core sinks inside a red giant or red supergiant, represent an excellent research target for understanding binary evolution. This review first provides a theoretical overview of the structure and evolution of massive TZOs; then focuses on observational discoveries related to massive TZOs, particularly HV2112 in the Small Magellanic Cloud; and finally summarizes current work and future prospects.

Keywords: Thorne-Żytkow Objects; neutron stars; compact binary evolution; red giants; red supergiants

1 Introduction

Thorne-Żytkow Objects (TZOs) were first proposed theoretically by Thorne and Żytkow [?]. According to theoretical predictions, a TZO consists of a degenerate neutron star core at the center of a red giant or red supergiant (in contrast to normal red giants or supergiants which lack such a neutron star core). Although TZOs differ from ordinary red giants and supergiants, their properties share many similarities in terms of chemical element abundances and spectra. Regarding the possibility of TZO formation, researchers have proposed various models and conclusions. Currently, it is widely accepted that TZOs can form in two distinct environments: (1) In a globular cluster, a neutron star collides directly with a normally evolving star (dwarf or giant), leading to mutual capture and merger. This collision may result from unstable mass transfer in a binary system, or from an asymmetric supernova explosion in which the newly formed neutron star is kicked toward its companion and captured [?]. (2) In a massive X-ray binary system, the evolution of the massive star may cause it to engulf its neutron star companion, producing a common envelope that gradually spirals inward until complete merger occurs. The former scenario produces low-mass TZOs, while the latter produces massive TZOs exceeding 14M [?], leaving a significant gap between these mass limits (8.5M –14M) that current models cannot perfectly explain. Many researchers have proposed different specific formation and evolution mechanisms for these two environments.

Observationally, TZOs are difficult to identify directly through their apparent characteristics because they closely resemble red giants or supergiants. However, the distinct elemental signatures produced by the rapid proton capture process (rp-process) and slow neutron capture process (s-process) provide a method for searching for TZO candidates. The most notable TZO candidate observed to date is HV2112 in the Small Magellanic Cloud (SMC) [**?**], whose candidacy is primarily based on abundance comparisons with ordinary red supergiants. In addition to HV2112, there are other TZO candidates and objects that may have experienced a TZO evolutionary phase. Section 2 focuses on the theoretical overview of massive TZO structure and evolution, including several important nuclear processes in stellar structure evolution, as well as the formation of massive TZOs and their various possible evolutionary outcomes. Section 3 focuses on observational discoveries of massive TZOs, including possible remnants after TZO evolution, particularly the chemical properties of HV2112 in the SMC, with analysis and interpretation through different theoretical frameworks. Section 4 summarizes current work and outlines future research directions.

2.1 Important Nuclear Processes

Theoretically, stable burning phases in sufficiently massive stars can produce elements up to the iron peak through nucleosynthesis. Heavier nuclei, having lower binding energy per nucleon than iron, cannot be generated through stable burning but instead require rapid neutron capture (r-process), slow neutron capture (s-process), or rapid proton capture (rp-process).

The s-process is a series of nucleosynthetic reactions occurring in stars, particularly on the Asymptotic Giant Branch (AGB). The s-process creates approximately half of the elements heavier than iron and plays a crucial role in galactic chemical evolution. In the s-process, the rate of neutron capture by atomic nuclei is slower than the β-decay rate. Isotopes in steady state capture neutrons, but the resulting radioactive isotopes decay to stable nuclei before another neutron capture occurs, thus moving isotopes along the valley of stability via β-stable pathways.

The r-process creates neutron-rich, iron-peak-heavy elements in core-collapse supernova or binary neutron star merger environments, also producing about half of the heavy elements beyond iron. It requires continuous rapid neutron capture starting from iron-group nuclei. The r-process occurs in explosive nucleosynthesis where high temperatures and enormous neutron fluxes after core-collapse supernovae or binary neutron star mergers make neutron capture rates much faster than β-decay rates, driving the process along the neutron drip line.

The rp-process is a sequence of proton captures by seed nuclei forming heavier elements. This nucleosynthetic process combines characteristics of both s-process and r-process, capable of synthesizing the heaviest elements, though its endpoint remains uncertain with current knowledge. The rp-process requires extremely high temperatures and hydrogen-rich environments, with initial nuclei possibly produced during CNO cycles. Potential sites for the rp-process are generally believed to be in binary systems with compact companions (low-mass black holes or neutron stars) undergoing violent accretion, where the companion is typically a hydrogen-rich star such as a red giant. The red giant supplies material for accretion onto the compact object. Since this material originates from the companion's surface, it is rich in hydrogen and helium. The strong gravitational field of the compact object accelerates the infalling material, which typically collides with other matter to form an accretion disk. Under these conditions, material accumulates on the companion's surface at extremely high temperatures, becoming electron-degenerate matter. Electron-degenerate matter in a hot atmosphere reaches a Kelvin-Helmholtz unstable state (primarily describing linear airflow instability), where temperature increases trigger thermonuclear explosions that produce the rp-process (see Figure 1 [Figure 1: see original paper]).

In summary, the s-process is generally believed to occur during helium burning in regions with relatively abundant high-energy neutrons, while the rp-process occurs where high-energy protons are relatively abundant, typically in binary systems with compact companions. The equilibrium structure of TZOs produces elements characteristic of the rp-process, which does not occur in normal red giants. Therefore, significantly enhanced abundances of corresponding elements can be found in TZOs, providing a method to distinguish them from red giants. The following sections provide a theoretical overview of massive TZOs, including their formation, evolution, and possible final outcomes. For completeness and fairness, this chapter is not limited to theories supporting TZOs but also includes relevant theories that challenge TZO formation. Before beginning, we establish a qualitative definition for convenience: in massive X-ray binary systems, the companion star that evolves to the neutron star stage first will be referred to as the "fat star."

2.2 The Birth of TZOs

Type II supernovae, also known as core-collapse supernovae, result from the violent explosions triggered by the collapse of massive stars. Type II supernovae can be further classified based on their post-explosion light curves. The spectra of Type II supernovae typically exhibit Balmer absorption lines, which are commonly used to distinguish them from Type I supernovae. Type IIP Supernovae are a subclass of Type II supernovae characterized by a distinct plateau structure in their declining light curves, representing a relatively slow brightness decrease over a period of time. Type IIn Supernovae feature relatively narrow hydrogen line widths.

Massive TZOs primarily form in massive X-ray binary systems [?]. Under normal circumstances, when the massive primary star completely fills its Roche lobe, the mass transfer rate exceeds the neutron star's Eddington accretion rate by several orders of magnitude. Consequently, most of the mass in the binary system cannot be fully accreted by the neutron star, and the excess mass forms an extended envelope around the neutron star that eventually fills the neutron star's Roche lobe. At this point, the massive X-ray binary system evolves into a common envelope phase, with the neutron star being engulfed by the fat star's envelope and spiraling inward toward the system's center due to gas drag. In the first evolutionary scenario of massive X-ray binaries, sufficient orbital energy is released during this process to completely eject the common envelope, leaving a very close binary with a period of 3–4 hours, containing a fat star with a helium-burning core greater than 3M and the original neutron star. Observations suggest that the fat star may undergo further supernova explosions, leaving a neutron star remnant without disrupting the binary system, eventually evolving into a very close double neutron star system. This evolutionary pathway demonstrates that some massive X-ray binaries can avoid merger during the common envelope spiral-in process. The formation process of TZOs is shown in Figure 2 [Figure 2: see original paper].

However, TZO research focuses on systems that do merge. In the second evolutionary scenario of massive X-ray binaries, if the energy is insufficient to eject the common envelope, the neutron star will reach the center and spiral in, ultimately forming a TZO. Comparing these two different systems, the former is more likely to become a double neutron star progenitor, while the latter is more likely to undergo complete merger and form a TZO. Another TZO formation mechanism (see Introduction) occurs after supernova explosions, where asymmetric supernova kicks cause the binary system to merge directly.

Early TZO research identified two structures: giant and supergiant outer layers, satisfying envelope mass constraints [**?**]. For giants, 97% of the energy comes from core accretion onto the envelope, while for supergiants, 95% of the energy comes from nuclear burning in the convective envelope. Compared to surface mass loss, core accretion plays the dominant role, so TZO lifetimes primarily depend on how quickly they consume their common envelopes. After losing the common envelope, they leave behind an isolated neutron star or black hole remnant. In binary formation scenarios, it is generally believed that after the spiral-in phase, material above the neutron core is continuously accreted onto the neutron star with sufficient angular momentum to spin it up to millisecond periods. Therefore, if a rapidly rotating neutron star remains, it could be a millisecond pulsar. Whether this mechanism can produce isolated millisecond pulsars depends primarily on how much mass is accreted and how angular momentum is redistributed within the envelope after the spiral-in phase.

2.3 The End of TZOs

Massive TZOs primarily support their envelopes through the rapid proton capture process (rp-process) near the neutron core, allowing them to be observed as red giants or red supergiants with peculiar chemical abundances. For example, HV2112 is considered a massive TZO candidate because its anomalous chemical signatures match theoretical predictions (though many studies have proposed alternative explanations, and this paper will specifically point out some flaws in using TZOs to explain HV2112). When massive TZOs exhaust the initial elements for the rp-process and mass loss reduces them below the mass required to sustain the rp-process, their structure becomes unstable and collapses, ultimately ending their brief lives in explosion.

Specifically, after nuclear burning ceases at the neutron core surface, surface material continues to contract while temperature rises continuously, releasing neutrinos and causing energy loss. Due to efficient neutrino cooling, accretion onto the neutron core is no longer limited by the Eddington rate but instead depends on the free-fall accretion rate. Related research suggests that effective convection in TZO envelopes causes them to rotate extremely rapidly [**?**]. When centrifugal forces become dominant, the free-fall accretion rate is correspondingly suppressed.

At this point, approximately 10^{-3}M of mass has been accreted onto the neutron core, but the neutron core has not yet collapsed into a black hole. A thin accretion disk will form around the central neutron core, with subsequent accretion times determined by uncertain viscosity in the accretion disk. Nevertheless, even maintaining super-Eddington accretion [**?**], the accretion rate remains much greater than 10^{-3}M a^{-1}.

Meanwhile, during this phase the accretion disk at the neutron core triggers large-scale jets. If super-Eddington accretion continues, several months or years after collapse, approximately 1M of material will be accreted onto the neutron star core, at which point the central neutron core collapses into a black hole. If the accretion disk still exists at this time, super-Eddington accretion persists and continues to produce large-scale jets. Subsequently, the TZO enters the explosion phase. For typical massive TZOs, their binding energy is on the order of 10^{40} J. For example, a TZO with 16M mass and a 1M neutron core has a binding energy of 5×10^{40} J.

During TZO collapse, a super-Eddington accretion disk may form near the central compact object, emitting large-scale jets. Because TZO binding energy is very small, these jets can easily be pushed back into the collapsing TZO and trigger an explosion. The observed properties of TZO explosions depend heavily on the energy released by the accretion disk, with several possible outcomes.

If accretion is suppressed shortly after the release of binding energy (10^{40} J), the explosion energy will not exceed 10^{40} J, and the explosion may be observed as a low-energy Type IIP supernova. Using the theory of Kasen and Woosley [**?**], the peak bolometric luminosity is expected to reach -7.1 mag and last approximately 900 days. Since this luminosity is comparable to that of the progenitor star, the TZO might appear to disappear without having exploded. The explosion energy is similar to that of failed supernova explosions [**?**], so a low-energy supernova might be confused with a TZO explosion. If the TZO is surrounded by dense interstellar medium, the ejected material will interact with it, possibly appearing as a low-luminosity Type IIn supernova. Currently observed Type II supernova explosions cannot be ruled out as possible products of low-energy TZO explosions, requiring further analysis of chemical abundances in their remnants.

However, if accretion is not suppressed and the disk wind persists, the accretion disk can release larger jets that increase the TZO's explosion energy to reach or even exceed supernova energies. Assuming standard energy conversion efficiency, the explosion energy could reach up to 10^{46} J, comparable to energies produced by large Type II supernovae or hydrogen-rich superluminous supernovae. This explosion would cause black hole formation, and with the black hole's formation, an intense jet would be produced. The exploding TZO might be observed as an extremely long-duration γ-ray burst [?]. If the jet can penetrate the envelope, it might also produce a transient superluminous supernova.

The TZO production rate in galaxies is approximately 2×10^{-4} a^{-1} [?], and the TZO explosion rate in galaxies is close to the production rate. Based on this rate, approximately one TZO explosion may occur for every 10,000 supernova explosions, comparable to the rate of superluminous supernovae. Since the predicted energy of TZO explosions may be similar to supernovae, distinguishing between TZO explosions and supernovae is a challenging task. The most effective method for distinguishing them lies in discriminating their metallicities. Late-stage supernovae produce strong metal lines from their progenitor's core, while TZOs do not produce such strong metal lines. Additionally, the peculiar abundance patterns in massive TZOs may provide important clues. Very few TZO candidates have been discovered to date, suggesting that if TZOs exist, their lifetimes are extremely short.

Possibly due to substantial mass loss, TZOs reach the lower mass limit for producing irp-process (intermittent rapid proton capture process) prematurely. When a TZO falls below this mass limit, the irp-process terminates and ends the TZO phase. If mass loss is the primary cause of irp-process termination in TZOs, TZO explosions should be more common. Due to the unique nature of TZO explosions, further observations are needed, particularly regarding the chemical signatures of remnants from Type II supernovae. With TZO explosions, large amounts of peculiar elements enter the interstellar medium, making this potentially a very important component of cosmic chemical evolution.

2.4 Challenges to TZO Formation Theory

Different models and viewpoints have always existed regarding TZO formation and evolution. Papish et al. [?] argue that if accretion from the neutron star can exceed the Eddington rate, large amounts of accretion energy will be channeled directly into jets that blow away the giant's envelope, preventing TZO formation through common envelope evolution (see Figure 3 [Figure 3: see original paper]). This theory employs the jet feedback model [?], where energy deposited by jets ejects the entire envelope and part of the core material, with strong jet-core interactions occurring in the final stages of common envelope evolution. Regarding the specific candidate HV2112, this viewpoint holds that it is not a TZO because its formation and evolution process cannot realistically occur.

Observable evidence supporting this argument can be obtained by identifying the specific sites of rapid neutron capture (r-process) nucleosynthesis. Elements in A6130 were born from relatively strong r-processes, and there are two different viewpoints regarding where this process occurs [?]: one believes it happens in binary neutron star mergers [?], while the other believes it occurs in jets from newly born, rapidly rotating neutron stars [?]. Specifically, in early studies of neutron stars and red supergiants, Taam et al. [?] believed that when a neutron star spirals into a red supergiant envelope, two outcomes are possible: envelope ejection and core-neutron star merger, but this did not consider jet effects.

Current understanding suggests that strong neutron star accretion produces jets. One model proposes that large amounts of r-process elements form in neutron star-generated jets, causing stellar explosions during common envelope evolution. Another classic model is based on the magnetorotational mechanism [?], where rapid core rotation amplifies magnetic fields, producing bipolar jets near the newborn neutron star that also cause explosions. However, this model requires stellar rotation rates far greater than those given by stellar evolution models, making it applicable only to very special cases. In summary, when a neutron star spirals into a red giant core and emits jets, intense r-process nucleosynthesis may occur. These jets cause energy to accumulate in the envelope and eventually explode the entire star. This represents a relatively rare evolutionary pathway that coincides with many facts regarding the discovery of these elements. During the spiral-in process of a neutron star with a red supergiant, the accretion rate is extremely large, far exceeding the Eddington rate, so large amounts of accumulated energy enter the envelope. Meanwhile, the spiraling neutron star releases jets that disperse the envelope, making it possible that a stellar core under such conditions cannot form a TZO through common envelope evolution.

3.2.1 Properties of HV2112

The most exciting development in TZO observations is the study of HV2112. In massive TZOs, the convective envelope extends almost to the neutron star surface, so extremely hot hydrogen burning synthesizes elements with high proton numbers through the irp-process. However, due to the very low TZO production rate and their very short lifetimes, the existence of TZOs observationally remains questionable.

HV2112 is the first observed TZO candidate, and its distance has been subject to different interpretations that lead to different hypotheses. The premise for HV2112 being a TZO candidate depends on its membership in the Small Magellanic Cloud (SMC) [?]. Early work suggested that if HV2112 were in the SMC, its proper motion would reach 3,000 km s^{-1}, far exceeding the SMC's escape velocity, leading to the conclusion that HV2112 is more likely a halo star in the Milky Way at a distance of about 3 kpc [?], meaning it would not have sufficient luminosity to be a red giant, let alone a TZO candidate. Subsequent research confirmed HV2112 as an SMC member [?], consistent with the SMC's eastern wing substructure, which shows evidence of star formation between 50–200 Ma, with young compact objects associated with HV2112. HV2112's radial velocity (157 km s^{-1}) matches the SMC's radial velocity (145.6 km s^{-1}), and its line-of-sight radial velocity is about 13 km s^{-1}, consistent with both halo stars and the SMC. In 2MASS color-magnitude diagrams, HV2112 clearly falls within the SMC's M-type supergiant region. Integrating this information—coordinates, proper motion, radial velocity—all conform to SMC membership, and optical measurements place it in the SMC supergiant range, providing strong evidence that HV2112 is a member of the SMC. Studies using Gaia's second data release also confirm that HV2112's proper motion is fully consistent with SMC membership, and its line-of-sight velocity matches, excluding all evolutionary scenarios placing HV2112 within a few kpc of the Sun.

TZOs represent a completely new theory of stellar structure, and the related irp-process is an innovative nuclear reaction model for stellar interiors. Currently, there is no good method to distinguish TZOs from ordinary M-type red supergiants based on appearance alone; the only distinguishing feature in observations is their atmospheric chemical element abundances. Due to the extremely high pressure at the interface between the neutron star core and the fully convective envelope, the irp-process produces many unusual chemical element abundances [**?**]. Although red supergiant spectra are dominated by titanium oxide (TiO) absorption lines, some special irp-process products should still be observable in TZO atmospheres, including Rb I, Sr I, Sr II, Y II, Zr I, Mo I [**?**]. Additionally, Li abundance in TZOs should greatly exceed normal values.

3.2.2 The Argument for HV2112 as a TZO

In studies of HV2112 [**?**], red supergiant atmospheric models are affected by atmospheric geometry, optical depth variations, mass loss effects, and chemical abundance variations in the host galaxy. To avoid biases from these atmospheric model assumptions, various studies accordingly measured equivalent width ratios of optical spectral lines for elements of interest. To search for unusual element abundances characteristic of TZOs, researchers compared abundances of elements expected to be significantly enhanced in TZOs (Li, Rb, and Mo) with those not expected to increase significantly (K, Ca, Fe, Ni).

When comparing TZO element ratios among red supergiants in the host galaxy, HV2112 in the Small Magellanic Cloud was found to have exceptionally high ratios in Rb/Ni, Li/K, Li/Ca, and Mo/Fe. Figure 4 [Figure 4: see original paper] presents all samples in the SMC (including HV2112) combined with normal Ni/Fe and K/Ca ratios for analysis, clearly showing significant enhancements of Rb, Li, and Mo in HV2112's atmosphere. In this figure, all samples are from the SMC, with effective temperature on the horizontal axis and element ratio values on the vertical axis. These ratios include those that should be significantly enhanced in TZOs and control ratios. Dark lines show the best-fit values for each element corresponding to different effective temperatures. HV2112's ratios are marked in red.

Figure 5 [Figure 5: see original paper] shows spectra of HV2112 and typical

SMC red supergiants, with HV2112's spectrum displaying prominent TZO characteristics. Although Mo or Rb can be observed in some stars and their presence attributed to the s-process, no previous observations or expected s-process theoretical scenarios can produce both elements simultaneously on a star with exceptionally high Li abundance. The presence of Li also provides another argument: stars undergoing s-process at low temperatures have not been found to have simultaneous Rb and Li enhancements [?]. These three elements have never been observed together in any s-process star. The strength of Ba II absorption lines can provide further consideration. Since Ba is a very common s-process product, this offers a method to test whether abundance enhancements in HV2112 result from s-process rather than irp-process [?], and HV2112's Ba II strength shows no stronger s-process signatures compared to other SMC red supergiants in the sample.

Calculations show Mbol = -7.82 ± 0.2, consistent with a red supergiant of initial mass 15M , far exceeding the maximum mass limit for AGB stars. Massive binaries with similar orbits are more common in metal-poor environments [?], predicting that TZO binary evolution may first appear in metal-poor environments like the Small Magellanic Cloud. However, some observed line ratios in HV2112 do not match expectations. Although the Rb/Ni ratio in HV2112 is far higher than measured in SMC red supergiants, the Rb/Fe ratio is normal. HV2112's Ni/Fe ratio is also normal compared to the red supergiant sample, ruling out excessively high Fe abundance. Features of Mo, Li, and Rb are evident but not significantly enhanced to the large abundance values predicted for TZOs [?]. Such relatively weak elemental enhancements may suggest HV2112 is in an early TZO phase or that its TZO existence phase is very brief [?]. HV2112's Ca/Fe ratio is also unusually high, but this abundance enhancement lacks theoretical explanation related to TZOs.

Any definitive detection of a TZO would provide direct evidence for a completely new stellar interior model while confirming the predicted fate of massive binary systems and the existence of nucleosynthetic environments that provide new channels for heavy element and Li production in the universe. However, HV2112 remains controversial. Besides TZOs, we list other possible stellar structures below. Although the main debate centers on whether HV2112 is a TZO or SAGB star, we also analyze the possibility of HV2112 being an AGB star and provide reasons for discarding this option.

3.2.3 The Argument for HV2112 as an AGB Star

Whether HV2112 is truly a TZO remains highly controversial, with some research suggesting HV2112 is an AGB star rather than a TZO. The judgment of HV2112 as a TZO is primarily based on the star having a very cool surface (lg(L/L) > 5) and surface enrichment in Li, Ca, and various irp-process elements.

Some new studies claim that after adopting new observational methods, HV2112's bolometric luminosity falls in the range lg(L/L) = 4.70–4.91 [?], lower than previous observations and consistent with AGB characteristics. After comparing HV2112's spectrum with late-type, high-luminosity stars in the SMC, no clear evidence was found for significant enhancements in Rb, Ca, or K, though Li abundance was significantly enhanced. Therefore, it is considered to be a 5M AGB star.

In previous studies [?], the Rb/Ni ratio clearly indicated significant Rb abundance enhancement, while the Rb/Fe ratio was normal and the Ni/Fe ratio was also normal, which is inconsistent. Additionally, the selected samples in that study had different effective temperatures and lg(g) values, while chemical element abundances are likely very sensitive to these parameters. The study also noted that spectral lines can be blanketed by TiO lines and are very sensitive to effective temperature and atmospheric structure; therefore, HV2112 cannot be directly identified as a TZO.

3.2.4 The Argument for HV2112 as an SAGB Star

Another possibility for HV2112 is that, due to its luminosity approaching or exceeding 10^5 L , it may be an SAGB star—a thermally pulsing star with an electron-degenerate O/Ne core undergoing the third dredge-up phase. Both TZOs and SAGB stars are extremely rare in the universe. To date, HV2112's atmospheric element abundances cannot distinguish between these two possibilities using the latest models. Enhancements in Mo and Rb abundances could be provided by the irp-process in TZOs [?] or by the s-process in SAGB environments [?]. Li abundance enhancement could also result from bottom burning in the common envelope. However, SAGB stars cannot synthesize Ca, while Ca might be produced in the final stage of TZO formation, making HV2112's significantly enhanced Ca abundance important.

Earlier studies [?] did not clearly discuss the possibility of SAGB stars. SAGB stars are stars with initial masses of 8–10M in their late evolutionary stages that, depending on assumptions about convective overshooting during helium burning, ignite their central carbon core before the second dredge-up occurs [?]. Intermediate-mass stars evolve through hydrogen core burning on the main sequence. When central hydrogen is exhausted, hydrogen burning moves to a shell and the star becomes a red giant. Its convective envelope deepens and dredges some hydrogen-burning products to the surface. When temperatures are sufficiently high, the 3α process enables helium burning in the core, convectively burning into carbon and oxygen. After core helium exhaustion, shell burning occurs just outside the hydrogen-burning shell. These double-shell burning stars lie on the AGB. In more massive AGB stars, when the deep convective envelope penetrates the temporarily exhausted hydrogen-burning shell, a second dredge-up occurs. This brings new hydrogen fuel to reignite the hydrogen shell just a few percent of a solar mass outside the helium-burning shell. The thinness of the helium-rich region, combined with the strong temperature sensitivity of the 3α reaction, leads to unstable helium burning in pulses, with third dredge-up occurring between pulses that brings helium-burning products to the surface, where slow neutron-capture isotopes can explain the observed elements heavier than Fe in HV2112. More massive SAGB stars ignite their carbon core before the second dredge-up and undergo thermal pulses and dredge-up processes in similar fashion. Before the second dredge-up, SAGB cores have higher masses, giving them early luminosities approaching those of red supergiants and TZOs. Once thermal pulses and third dredge-up begin, the core and resulting luminosity grow more slowly. Among all observed chemical element abundances, both SAGB and TZO can explain the enhancements, with Ca being the exception.

Both SAGB and TZO are rare in the universe. At SMC metallicities, SAGB formation masses are 6.5–8M . SAGB lifetimes are short, and because their progenitor lifetimes are also short, approximately only one SAGB exists among every 1,000 stars of appropriate mass. Among approximately 250 star clusters with ages around 300 Ma, Glatt et al. [?] found average cluster masses of about 4,000M , with SAGB formation possible only in clusters with total masses around 10^6 M . Integrating these data yields a current total of about one SAGB in the SMC, which within calculation precision matches HV2112 being the only SAGB discovered to date in the SMC.

HV2112's high Rb and Mo abundances could be produced by the irp-process in TZOs [?] or by the s-process in SAGB environments [?]. The latter initially forms lighter elements, with Rb and Mo both belonging to the lighter elements formed in the s-process. Later, with increasing neutron exposure, heavier elements including Ba are formed. Turning attention to Li, Li can be produced in the early evolution of AGB stars through hot bottom burning [?]. After the second dredge-up occurs, SAGB envelope base temperatures can reach 6 × 10^7 K, enabling hot bottom burning and Li synthesis. First, ^{7Be} can be produced through the reaction: ^{3He} + ^{4He} → ^7 Be + γ. Then ^{7Be} can capture an electron to form ^{7Li}: ^{7Be} + e^- → ^7 Li + . Some Li produced by hot bottom burning can be transported to the surface by convection, causing significant Li abundance enhancement in a short time, increasing by more than 10 times in many models. Li that remains mixed or in the hot burning region is subsequently destroyed by proton capture: ^{7Li} + ^{1H} → 2^{4He}.

Since Li is clearly enhanced before any thermal pulses, SAGB surfaces are Li-rich before s-process enrichment. In the first few pulses, lighter s-process isotopes are transported to the surface while most previously produced Li is destroyed. s-process element enhancement continues for 10^{4-10}5 a [?], depending on initial mass and envelope convection. The Li-rich phase lasts 10^5 a in 6M stars, indicating that Li and Rb can coexist with relatively high abundances. TZOs can also synthesize Li through the same mechanism, in this case occurring in the convective envelope above the degenerate core, but without process (3) due to convection. In a standard model, Li abundance can increase for 10^5 a initially and continue increasing for 10^6 a, exceeding the maximum lifetime considered possible for TZOs. Therefore, finding Rb, Mo, and Li simultaneously in TZOs is also possible.

Notably, Ca abundance enhancement was discovered in HV2112. Ca production occurs in the final stage of stellar core life through α-particle capture in photodisintegration processes, where α-capture converts Si^{28} to Ni^{56} before supernova explosion. No nucleosynthesis that enhances Ca has been found in either SAGB or TZO models. In earlier SAGB phases, no period reaches conditions for internal Ca synthesis, so this can only be explained as accidental external contamination. For TZOs, one possibility is that when the degenerate core merges with the neutron star, conditions in the accretion disk can reach higher temperatures conducive to Ca production. Metzger [?] calculated nucleosynthesis in accretion disks from disrupted white dwarfs. For a 0.6M white dwarf (the model closest to HV2112 in his calculations), approximately 10^{-3}M of Ca escapes from the accretion disk, exceeding the mass needed to pollute the envelope and significantly enhance Ca abundance on HV2112's surface. Even considering mass loss from stellar winds, at least 1/10 of the Ca mass would pollute the envelope. This scenario matches other known relativistic accretion disk systems and can explain the Ca abundance increase. However, this research still has significant limitations: the Metzger model used is only for white dwarfs, with only 1/10 the accretion rate of neutron stars, and it depends on the assumption that a stable neutron star continues as the central object rather than collapsing into a black hole.

3.3 Observational Analysis of HV2112-like Stars in the Magellanic Clouds

Meanwhile, other researchers [?] have explored HV2112 from another perspective. HV2112 has a 600-day photometric period, with apparent magnitude changes during the cycle [?]. Within one period, HV2112 shows two peaks. Based on these characteristics, 11 stars with properties very similar to HV2112 (HLOs) can be selected in the Magellanic Clouds (SMC and LMC) where HV2112 resides, and their observational properties, physical properties, production rates, and lifetimes can be analyzed and predicted.

HLOs have apparent magnitude amplitudes greater than 2.5, periods longer than 400 days, average absolute magnitudes between -2.5–5 mag, and infrared colors indicating oxygen-rich atmospheres. HLOs have effective temperatures of 3,250–3,600 K, luminosities lg(L/L) of 4.15–5.15, mass loss rates of 1\$ $\times 10^{-7} M\odot a^{-1} to 4\times$ \$10^{-6} M a^{-1}, and expected masses of 6–11M .

Considering that HLOs may be stars of 6.5–11M (SAGB evolutionary path) or evolved from massive X-ray binary systems (TZO evolutionary path), the HLO phase lifetime is 10^4 a, matching the expected SAGB phase lifetime and an order of magnitude smaller than the expected TZO phase lifetime.

Analysis of HLO categories yields the following conclusions: (1) Since HLO properties differ significantly from observed properties of RSGs (magnitude variations and colors) and theoretical predictions, HLOs clearly do not belong to red giants. (2) Comparison with AGB properties shows that one star in the sample (LMC-3) fits very well and can be considered an AGB star, while the remaining 10 samples differ from AGBs in many properties, exceeding typical AGB masses and luminosities. (3) HLOs' high luminosities and masses match SAGB predictions, but in late SAGB evolution, mass loss rates or superwinds exceed 10^{-5} M a^{-1} [?], which is not observed in HLOs that show loss rates of 10^{-7} to 10^{-8} M a^{-1} [?]. Doherty et al. [?] propose that an SAGB in the superwind phase should satisfy one of two conditions: a period exceeding 850 days, or a period exceeding 500 days with C/O ratio greater than 1. Since all HLOs have periods shorter than 850 days and infrared colors indicate oxygen-rich atmospheres, HLOs may still be in the carbon core burning phase, not having reached the superwind phase. Theoretical mass loss rates before the superwind phase match HLOs. Both HLOs' current masses and expected lifetimes match SAGB evolutionary predictions. Therefore, if HLOs are in the pre-superwind carbon burning phase, they match SAGB predictions. Since only one confirmed SAGB candidate exists to date, this discovery would significantly increase the known number of SAGBs. (4) HLOs' effective temperatures, mass loss rates, and luminosities all match TZOs very well. However, there is a major discrepancy between TZO expectations and HLO observations: a stable massive TZO should have mass not less than 14M [?]. Pulsation model analysis of HLOs' luminosity, effective temperature, and period shows current masses of 6–11M , below the mass limit. When a massive TZO maintains nuclear fusion below its mass limit, it will experience neutrino losses and ultimately destabilize [?]. Therefore, only three possibilities exist: the mass limit for massive TZOs needs revision, observed HLO masses are underestimated, or HLOs are not TZOs.

4.1 Discussion

TZOs are theoretically predicted exotic objects composed of a red giant with a neutron star core inside. Massive TZOs have total masses not less than 11.5M and are primarily powered by nucleosynthetic reactions occurring at the base of the convective envelope. TZOs are believed to evolve from very close massive binary systems. When the neutron star forms, the more massive companion evolves to the red giant phase. After a series of evolutionary stages, the companion's expanded envelope becomes a common envelope, and the neutron star spirals into the companion's center. Another possibility is that the neutron star receives a kick from a supernova explosion and moves directly toward its companion, eventually being engulfed.

TZO energy sources are primarily generated by the irp-process, producing unique elements characteristic of this process. The existence of TZOs in the universe has long been debated and urgently requires observational resolution. However, due to their very short lifetimes and stringent formation conditions, TZOs are expected to be extremely rare. Observationally, TZOs are very similar to red supergiants in many aspects, making identification a huge challenge. Only by detecting detailed chemical signatures of TZO candidates is identification possible. For example, chemical element signatures produced by the irp-process—Mo, Ru, Th, Pd, Ag—should be enhanced by more than 1,000 times normal levels. A second characteristic is enhanced Li abundance.

In Levesque et al.'s [?] study of HV2112, HV2112 has an effective temperature of about 3,450 K, apparent magnitude of 13.7 mag, and absolute magnitude of -7.82 mag, exceeding the Hayashi limit for SMC stars and the limit for ordinary AGB stars. Since observed elements are demonstrated through ratio comparisons rather than absolute values reaching the quantities predicted by irp-process, using ratios creates many potential problems. For example, if the comparison element has extremely low abundance, the supposedly high-abundance element may not actually be particularly abundant. Meanwhile, the study's self-consistency remains problematic, as the ratios between corresponding elements are difficult to reconcile, representing a drawback of using element ratios to demonstrate abundances. The study also reveals other issues, such as elemental enhancements being much smaller than predicted, though this could be due to HV2112 being relatively young. Additionally, the high Ca/Fe ratio discovered in the study is not predicted by current models. In summary, the main research claiming HV2112 as a TZO has many deficiencies.

4.2 Outlook

Future research and detection should pay greater attention to specific abundance details, detecting elements produced by the irp-process and the consumption of daughter elements. Typical candidates like HV2112, interpreted as both SAGB and TZO, remain controversial. To distinguish TZOs from SAGBs, Mg—a product of carbon core burning associated with SAGBs—becomes crucial. Observations of core collapse are urgently needed in this regard. There is also room for improvement in previous studies; future calculations using specific element abundances instead of element ratios will make results more convincing, though specific abundance measurements also have the potential to rule out HV2112 as a TZO. Everything awaits further observation and exploration.

On the other hand, O'Grady et al. [?] explored TZOs from another perspective, pointing to another possibility. Notably, there is a mass gap for TZOs between 8.5–14M . Therefore, the mass limit for massive TZOs capable of irp-process reactions is greater than all HV2112-like stars in the Magellanic Clouds. In current models, the mass limit for massive TZOs is jointly determined by convective efficiency, mixing length (MLT) parameters, and neutron star mass. Cannon [?] found that adjusting given assumptions can lower the mass limit to 10–11M . However, further exploration of TZOs clearly requires more detailed revisions to convective models.

It should also be noted that there is currently no TZO model directly related to pulsation periods. Therefore, for broader research and observations, a detailed stellar structure model satisfying luminosity lg(L/L) of 4.5–5.1 and periods longer than 500 days needs to be developed.

In summary, we hope this review will inform more researchers with observational capabilities about this celestial object and encourage them to invest observation time in searching for TZOs. We also hope theorists will become interested in TZOs, as since their proposal in 1977, many different models and conclusions have been proposed regarding their formation possibilities, pathways, and evolution, all requiring further analysis and refinement. On the other hand, because TZOs share very similar observational characteristics with red giants or red supergiants, finding and confirming candidates is very challenging, requiring mature and detailed theoretical predictions of observational features as a prerequisite. The future of TZO research is full of challenges and has tremendous driving force for binary system research and stellar structure modeling. More work and exploration are indispensable, both theoretically and observationally.

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