New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry
Proceedings IAU Symposium No. 307, 2014
G. Meynet, C. Georgy, J. H. Groh & Ph. Stee, eds.

doi:10.1017/S1743921314006279

Discovery of a Thorne-Żytkow object candidate in the Small Magellanic Cloud

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Abstract. Thorne-Żytkow objects (TŻOs) are a theoretical class of star in which a compact neutron star is surrounded by a large, diffuse envelope. Supergiant TŻOs are predicted to be almost identical in appearance to red supergiants (RSGs), with their very red colors and cool temperatures placing them at the Hayashi limit on the H-R diagram. The only features that can be used at present to distinguish TŻOs from the general RSG population are the unusually strong heavy-element and lithium lines present in their spectra. These elements are the unique products of the stars fully convective envelope linking the photosphere with the extraordinarily hot burning region in the vicinity of the neutron star core. We have recently discovered a TŻO candidate in the Small Magellanic Cloud. It is the first star to display the distinctive chemical profile of anomalous element enhancements thought to be characteristic of TŻOs; however, up-to-date models and additional observable predictions (including potential asteroseismological signatures) are required to solidify this discovery. The definitive detection of a TŻO would provide the first direct evidence for a completely new model of stellar interiors, a theoretically predicted fate for massive binary systems, and never-before-seen nucleosynthesis processes that would offer a new channel for heavy-element and lithium production in our universe.

Keywords. stars: peculiar, supergiants, variables

1. Introduction

Thorne-Żytkow objects (TŻOs) are a class of star originally proposed by Thorne & Żytkow (1975, 1977), comprised of a neutron star core surrounded by a large and diffuse envelope. They are expected to form as the product of a dual-massive-star binary, with the neutron star forming when the more massive star explodes as a supernova. During subsequent evolution of the system, the expanding envelope of the lower-mass companion may lead to a common envelope state and the spiral-in of the neutron star into the companion's core (Taam *et al.* 1978). Alternately, Leonard *et al.* (1994) propose that a TŻO may be produced when a newly-formed neutron star receives a supernova 'kick' velocity in the direction of its red supergiant (RSG) companion and becomes embedded.

TŻOs represent a completely new theoretical class of stellar object, offering a novel model for stellar interiors and an example of unique nucleosynthetic processes. However, there has never been a positive observational identification of a TŻO. They are predicted to be virtually indistinguishable from luminous M-type RSGs, lying at the Hayashi limit (Hayashi & Hoshi 1961) and showing signs of excess mass loss. To date, the only predicted observational signature of a TŻO is an unusual set of atmospheric chemical abundances, produced by the 'interrupted rapid-proton' process or *irp*-process that is uniquely possible in a stellar interior combining a neutron star core and a completely convective envelope (e.g. Zimmerman 1979; Biehle 1991; Cannon 1993; see also Wallace & Woosley 1981). Several specific *irp*-process elements should be observable in a TŻO atmosphere, including lines of Rb I and Mo I (Biehle 1994). ^{7}Li should also be over-abundant in TŻOs due to the ^{7}Be-transport mechanism, which is similarly dependent on the star's internal structure (e.g. Cameron 1955; Podsiadlowski *et al.* 1995). While previous searches have been made for TŻOs, none have observed a star with a chemical profile attributable to a TŻO interior (Vanture *et al.* 1999; Kuchner *et al.* 2002).

Here we present our observations of the TŻO candidate HV 2112 in the Small Magellanic Cloud. This star exhibits the distinctive set of anomalous element enhancements thought to be produced by processes unique to TŻOs. We discuss our sample, observations, and analyses (Section 2), discuss the properties of HV 2112 (Section 3), and consider the implications and potential for future work on TŻOs (Section 4).

2. Observations, Reduction, and Analysis

We constructed our sample of 22 SMC RSGs from objects observed in our past effective temperature ($T_{\rm eff}$) studies (Levesque *et al.* 2006) and additional stars with 2MASS photometry and colors consistent with RSGs ($K < 8.9$, $J - K > 1$). Closely-orbiting massive binaries are more common at low metallicities (Linden *et al.* 2010), making the predicted binary progenitor scenarios for TŻOs more likely in metal-poor host environments such as the SMC (log(O/H) + 12= 8.0, van den Bergh 2000).

Our observations were carried out using the Magellan Inamori Kyocera Echelle (MIKE; Bernstein et al. 2003) and Magellan Echellete (MagE; Marshall *et al.* 2008) spectrographs on the Magellan 6.5-meter Clay telescope at Las Campanas Observatory on 13-15 Sep 2011. We obtained high-resolution spectra with MIKE (using the $0'.7 \times 5'$ slit with 2×2 binning, 'slow' readout, and the standard grating settings to give $R \sim 42,000$) for the purpose of measuring line ratios, as well as lower-resolution MagE spectra (using the $1''$ with 1×1 binning and 'slow' readout) for the purpose of producing flux-calibrated spectrophotometry that could be used to determine contemporaneous physical properties for our stars. Our observations were generally performed with seeing $\lesssim 1''$ and airmasses $\lesssim$1.5; our MagE spectra were taken at the parallactic angle, and spectrophotometric standards were observed for flux calibration. The MIKE and MagE data were reduced using standard IRAF echelle routines and the `mtools` package (see Massey *et al.* 2012).

To search for signs of anomalous TŻO-like element enhancements in our spectra, we compared the equivalent widths of Li, Rb, and Mo absorption features - all elements expected to be enhanced in TŻOs - to those of nearby spectral features where no significant enhancements were previously predicted, such as K, Ca, Fe, and Ni (Cannon 1993; Biehle 1994; Podsiadlowski *et al.* 1995; however, see also Tout *et al.* 2014). However, line blanketing effects in RSG spectra completely obscure the continuum, rendering traditional measurements of absorption impossible. We therefore adopt the 'pseudo-equivalent width" method detailed in Kuchner *et al.* (2002), and determined pseudo-equivalent width measurements for our lines of interest with systematic errors of $\lesssim$5%.

We calculated the the Rb I λ7800.23/Ni I λ7797.58 (Rb/Ni) and Rb I λ7800.23/Fe I λ7802.47 (Rb/Fe) line ratios to probe the relative Rb enhancement in our stars; the Li I λ6707.97/K I λ7698.97 (Li/K) and Li I λ6707.97/Ca I λ6572.78 (Li/Ca) ratios for the relative Li enhancement; and the Mo I λ5570.40/Fe I λ5569.62 (Mo/Fe) ratio for the relative Mo enhancement. To ensure that our ratios were truly probing abundances anomalies in TŻO products rather than variations in our comparison features, we also

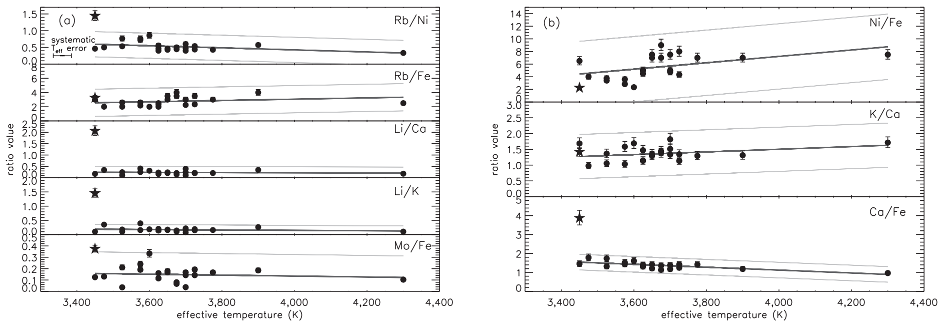

Figure 1. $T_{\rm eff}$ vs. measured line ratios for our SMC RSGs (circles) and HV 2112 (stars). The ratios include features predicted to be enhanced in TŻOs (a) as well as our 'control' features (b). A dark grey line shows the best linear fit for each line ratio as a function of $T_{\rm eff}$, while light grey lines mark the 3σ deviations from the fit that encompass 99.7 per cent of a normally-distributed sample. Error bars for each point illustrate the systematic errors of $\lesssim 5\%$.

calculated Ni I λ7797.58/Fe I λ7802.47 (Ni/Fe), K I λ7698.97/Ca I λ6572.78 (K/Ca), and Ca I λ6572.78/Fe I λ65569.62 (Ca/Fe) ratios for our stars.

We compared the line ratios for our stars relative to their measured $T_{\rm eff}$. We then determined the best linear fit for each set of ratios as a function of $T_{\rm eff}$, and calculated the 3σ variations from these fits that should encompass 99.7% of a normally-distributed sample. Following this method, we considered a ratio to be statistically anomalous if it fell outside the 3σ range. For a more detailed discussion of our observations, reductions, and analysis techniques please see Levesque *et al.* (2014).

3. The TŻO Candidate HV 2112

We found that one star, HV 2112, has anomalously high values of Rb/Ni, Li/K, Li/Ca, and Mo/Fe. The ratios measured for our full sample, including HV 2112, are shown in Figure 1. These ratios present clear evidence of Rb, Li, *and* Mo enhancement in the star's atmosphere, a combination thought to be possible as a result of the exotic stellar interiors of TŻOs. A comparison of the HV 2112 spectrum to a 'typical' SMC RSG is shown in Figure 2 (left); the HV 2112 spectrum exhibits notably stronger TŻO features. We also measure an atypically high Ca/K ratio; recent work suggests that Ca may be produced in the final stages of TŻO formation (Tout *et al.* 2014).

Observations of the Ca II triplet in the HV 2112 allowed us to measure a radial velocity (RV) of $\sim 157\,\mathrm{km\,s^{-1}}$, consistent with this star being a member of the SMC rather than a foreground dwarf (Neugent *et al.* 2010). From fitting a MagE spectrum of HV 2112 with a MARCS stellar atmosphere model (Gustafsson *et al.* 2008; see Figure 2, right), we determined a $T_{\rm eff}$ of 3450 K and a spectral type of M3 I, along with a V magnitude of 13.7 ± 0.1. Correcting for the SMC distance modulus of 18.9 (van den Bergh 2000) and the $T_{\rm eff}$-dependent BC in V (Levesque *et al.* 2006) we determined an $M_{\rm bol} = -7.82 \pm 0.2$; this corresponds to a initial mass of $M \sim 15\,M_\odot$ (Maeder & Meynet 2001). We also observed an excess amount of visual extinction in the direction of HV 2112 ($A_V \sim 0.4$ as compared to the average $A_V = 0.24$ for SMC OB stars assuming$R_V = 3.1$; Cardelli *et al.* 1989; Massey *et al.* 1995) and a slight flux excess ($\lesssim$10 $\mathrm{ergs\,s^{-1}\,cm^{-2}\,\AA^{-1}}$) in the near-UV. Both of these features are thought to be signatures of excess circumstellar dust associated with strong mass loss in RSGs (Levesque *et al.* 2005; Massey *et al.* 2005). Finally, past work identified HV 2112 as photometrically and spectroscopically variable (Payne-Gaposchkin & Gaposchkin 1966; Wood *et al.* 1983; Reid & Mould 1990; Smith

https://doi.org/10.1017/S1743921314006279 Published online by Cambridge University Press

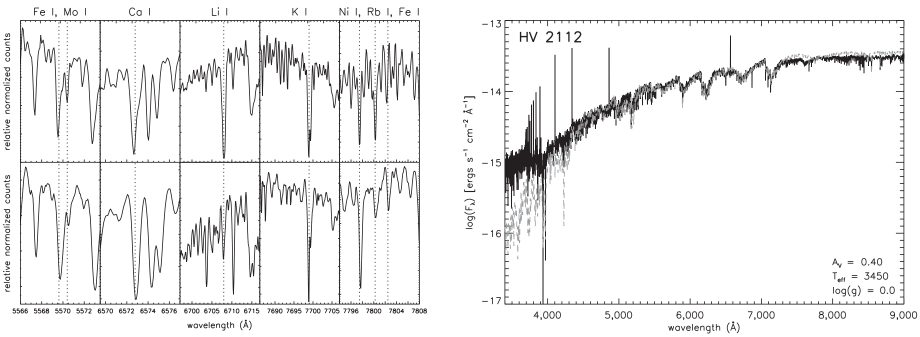

Figure 2. Left: spectral features of HV 2112 (a-e) and [M2002] SMC 005092 (f-j) used in our analyses. [M2002] SMC 005092 is a 'typical' SMC RSG with $T_{\rm eff} = 3475\,$K, comparable to the 3450 K $T_{\rm eff}$ we measure for HV 2112. Spectra are from our MIKE observations and have been corrected to rest-frame. Wavelengths of key absorption features are marked as vertical dashed lines. **Right**: MagE spectral energy distribution of HV 2112 (solid black line) and the best-fit MARCS stellar atmosphere model (dashed gray). The strong Balmer emission in the HV 2112 spectrum is clearly visible, along with the near-UV excess and near-IR deficiency typical of circumstellar dust effects (Levesque *et al.* 2005; Massey *et al.* 2005).

et al. 1995), properties predicted for TŻOs (Thorne & Żytkow 1977; van Paradijs *et al.* 1995).

Rb and Mo have been individually observed in stars and attributed to the *s*-process; however, there are no observed or predicted examples of the *s*-process producing both in a single star along with additional Li enhancement. Simultaneous Rb and Li enhancement is not observed in cool *s*-process stars (e.g. García-Hernández *et al.* 2013), and the combination of Rb, Mo, and Li has never been observed in any other cool massive star. Futhermore, while Rb, Mo, and Li can all individually be produced in super-asymptotic giant branch (SAGB) stars as well as TŻOs (through a combination of the *s*-process and hot bottom burning), an SAGB star cannot synthesize their own Ca and would not produce the Ca enhancement seen in HV 2112 (Tout *et al.* 2014). Finally, Ba is a common *s*-process product but we see no signs of Ba enhancement in the HV 2112 spectrum (see Vanture *et al.* 1999). Combined, our observed element enhancements and physical properties of HV 2112 strongly support its classification as a TŻO candidate.

However, HV 2112 does exhibit several unusual spectral features not previously predicted to be associated with TŻOs. The spectrum exhibit strong hydrogen Balmer emission features than extend from Hα out to H18 (see Figure 2, right) and display a Balmer *increment* (with Hδ as the strongest feature followed by Hγ, Hβ, and Hα) similar to that seen in M-type Mira variables. In Miras, this inverted Balmer emission is thought to be produced by non-LTE radiative transfer effects in the hydrogen lines from formation in a shocked atmosphere (Castelaz *et al.* 2000), with shocks generated by pulsation and propagating through the atmosphere. While the origin of these Balmer emission features in HV 2112 remains unclear, it is likely that the photometric and spectroscopic variability associated with HV 2112 could produce similar pulsationally-driven shocks.

In addition, while the Rb/Ni ratio in HV 2112 is far higher than the average ratio measured for SMC RSGs, the Rb/Fe ratio is quite typical. The Ni/Fe ratio in HV 2112 is also typical of the RSG sample, precluding the possible explanation of a Fe overabundance. The Mo, Li, and Rb features do not, at a glance, exhibit the extremely increased strengths one might expect based on the predicted enhancements for TŻOs (Cannon 1993; Biehle 1994; Podsiadlowski *et al.* 1995); however, relatively weak enhancements could be indicative of an early or short-lived TŻO phase (Thorne & Żytkow 1975, 1977;

Podsiadlowski *et al.* 1995). Convection models for massive star envelopes (particularly at low temperatures) have also advanced significantly in recent years, suggesting that the predicted enhancements for TŻOs could potentially be altered. It is clear that new models of TŻOs are needed; future theoretical work will likely provide updated predictions of element enhancements as well as additional identifying observables that can be used to test whether HV 2112 is indeed a bona fide TŻO.

EML is supported by Hubble Fellowship grant HST-HF-51324.01-A from STScI, which is operated by AURA under NASA contract NAS5-26555. PM acknowledges support from NSF grant AST-1008020. ANŻ thanks the Mitchell Family Foundation for support and Texas A&M University and Cook's Branch Nature Conservancy for their hospitality.

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Discussion

Grevesse: Why do you not use spectral synthesis around your lines rather than equivalent widths measured with a "pseudo-continuum"?

Levesque: High-resolution modeling of RSG atmospheres is subject to a number of physical complexities, including treatments of atmospheric geometry, optical depth variations, mass loss effects, and host galaxy abundance variations. To avoid potential biases introduced by the assumptions inherent to atmospheric modeling, we instead simply calculated equivalent width ratios for our spectral lines of interest and compared the resulting ratios across our entire sample to identify outliers. This allowed us to do a direct and consistent comparison that is independent of any modeling assumptions.

van Belle: Why doesn't the formation of a TŻO result in explosive detonation of the system? This seems like the ingredients of a cataclysmic variable.

Levesque: This is definitely a good question, and one that we're hoping to explore further in future work with formation models! For now, the Taam *et al.* (1978) and Leonard *et al.* (1994) papers detailing the two most commonly-cited massive binary formation mechanisms are probably the best resources for answer this. An interesting consideration along these lines is whether there would be some kind of non-terminal eruptive event or other observable signature during the actual formation process of a TŻO, and this will also hopefully be addressed by future models.

Meynet: Do we have any information about the rotation rate of the TŻO candidate?

Levesque: We unfortunately don't have estimates of this from our observations, but future work on binary merger models for producing TŻOs would likely be one means of predicting what kind of surface rotation rate we would expect to see.

Groh: Have you had a chance to look at the circumstellar environment of this object, e.g. in the mid-IR? Also, are you able to quantify $\dot{M}$ at this point?

Levesque: We haven't yet examined the circumstellar environment of HV 2112 in the mir-IR, and we can't quantify $\dot{M}$ with our current data. Imaging of the circumstellar environment would certainly be extremely interesting both for studying the mass loss properties and for seeking out any potential remnants of a recent supernova that could have produced the core neutron star.

Khalack: Have you taken into account the NLTE effects that can contribute to the formation of line profiles that belong to Li, Ru, Mo, Y, etc.?

Levesque: This isn't something we have examined directly; our ratio determinations are independent of any modeling assumptions, so NLTE effects are not a primary concern for this work. However, these effects would of course be important in future modeling of TŻO atmospheres!

Khalack: How many lines have you used to determine an average ratio of equivalent widths (for two elements)?

Levesque: We do not determine an "average ratio" of equivalent widths for two elements; instead, we simply measure the ratio of equivalent widths for two spectral features, one from each element that we are interested in, and compare the individual ratios from each star in our sample to identify any anomalous ratios. This is discussed in more detail in the above proceeding

Anderson: Given the spectroscopic variability you mentioned, have you considered photometric time-series from the EROS, OGLE, and MACHO surveys? Doing so could help find additional differences to RSGs, semi-regular variables, and Miras.

Levesque: This star has been included in a number of different optical and IR surveys and has long been identified as a photometric variable; we haven't yet examined this data in detail but agree that it would be an interesting approach for potentially identifying other similar TŻO candidates in the future and better understanding HV 2112 in particular.

Emily Levesque

Alex de Koter asking a question

https://doi.org/10.1017/S1743921314006279 Published online by Cambridge University Press