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A critical re-evaluation of the Thorne–Żytkow object candidate HV 2112

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ABSTRACT

It has been argued in the literature that the star HV 2112 in the Small Magellanic Cloud (SMC) is the first known example of a Thorne–Żytkow object (TŻO), a red supergiant with a degenerate neutron core. This claim is based on the star having a high luminosity ($\log(L/\mathrm{L}_{\odot}) \gtrsim 5$), an extremely cool effective temperature, and a surface enriched in in lithium, calcium, and various *irp*-process elements. In this paper we re-examine this evidence, and present new measurements of the stellar properties. By compiling archival photometry from blue to mid-infrared for HV 2112 and integrating under its spectral energy distribution, we find a bolometric luminosity in the range of $\log(L/\mathrm{L}_{\odot}) = 4.70$–$4.91$, lower than that found in previous work and comparable to bright asymptotic giant branch (AGB) stars. We compare a VLT+XSHOOTER spectrum of HV 2112 to other late-type, luminous SMC stars, finding no evidence for enhancements in Rb, Ca, or K, though there does seem to be an enrichment in Li. We therefore conclude that a much more likely explanation for HV 2112 is that it is an intermediate mass ($\sim 5\,\mathrm{M}_{\odot}$) AGB star. However, from our sample of comparison stars we identify a new TŻO candidate, HV 11417, which seems to be enriched in Rb but for which we cannot determine a Li abundance.

Key words: stars: abundances – stars: individual: HV 2112 – stars: peculiar – supergiants.

1 INTRODUCTION

Thorne–Żytkow objects (TŻOs, Thorne & Żytkow 1975, 1977) are a theoretical class of stellar object in which a neutron star sits within the diffuse envelope of a supergiant star. There are various suggested formation channels, most of which involve the merger of a binary system (e.g. Thorne & Żytkow 1977; Taam, Bodenheimer & Ostriker 1978). These objects are thought to be extremely rare, with as few as 20–200 TŻOs predicted to exist in the Galaxy at present (Podsiadlowski, Cannon & Rees 1995), though some authors have doubted whether such an object could survive the merger with the envelope intact (Papish, Soker & Bukay 2015).

Identifying a TŻO is challenging as it is expected that they would be virtually indistinguishable from normal red supergiants (RSGs) close to the Hayashi limit (Thorne & Żytkow 1977). They are expected to be highly luminous ($\log(L/\mathrm{L}_{\odot}) \gtrsim 5$), have cool effective temperatures (T_{eff}, $\lesssim$3000 K), and enriched in interrupted rapid portion (*irp*) processed elements, such as rubidium and molybdenum. They are also expected to be enriched in lithium as helium burning takes place at the base of the convective zone (Podsiadlowski et al. 1995). These elements are not expected to be enhanced in normal RSGs, so identifying a TŻO candidate relies strongly on the ability to measure the abundances of these heavy elements.[1]

HV 2112 was speculated to be a TŻO in Levesque et al. (2014) (hereafter L14) and has now been confirmed as member of the Small Magellanic Cloud (SMC) from its proper motion in Gaia-DR2 (Gaia Collaboration et al. 2018; McMillan & Church 2018) after a brief controversy over its distance (Maccarone & de Mink 2016). The claim by L14 was based on three pieces of evidence. Firstly, L14 determined a high luminosity ($\log(L/\mathrm{L}_{\odot}) = 5.02$) for HV 2112, above that expected for asymptotic giant branch (AGB) stars. Secondly, it was argued that the star's surface was enriched in molybdenum, rubidium, lithium, and, unexpectedly, calcium. Finally, HV 2112 has a late spectral type in comparison to the SMC average for RSGs.

Tout et al. (2014) discussed in depth the possibility of whether or not HV 2112 could instead be a superasymptotic giant branch star, a class of star that is also expected to exhibit enhanced lithium and have a high L_{bol}. A finely tuned model was required to explain the *irp* processed elements. Interestingly, Tout et al. showed that an

[1]In the original papers (Thorne & Żytkow 1975, 1977), a low-mass TŻO was also proposed. These objects would appear cooler than typical RSGs and potentially be dynamically unstable, but would not show the abundance anomalies or higher luminosities expected for high-mass TŻOs making them virtually indistinguishable from AGB stars.

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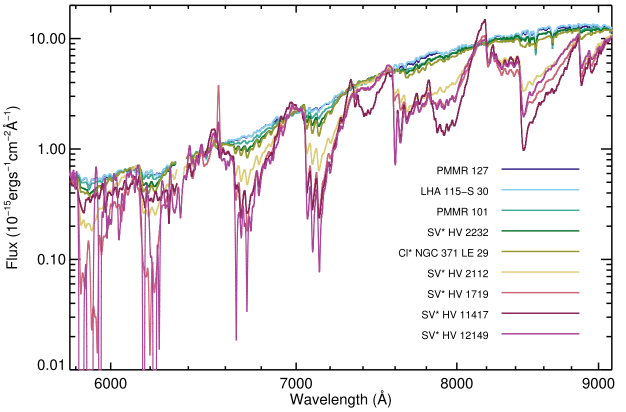

Figure 1. Spectral energy distributions of the stars in our sample. The spectrum of HV 2112 is flux-calibrated, whereas the other spectra are normalized according to the flux of HV2112 in the relatively line-free regions in between the TiO bands.

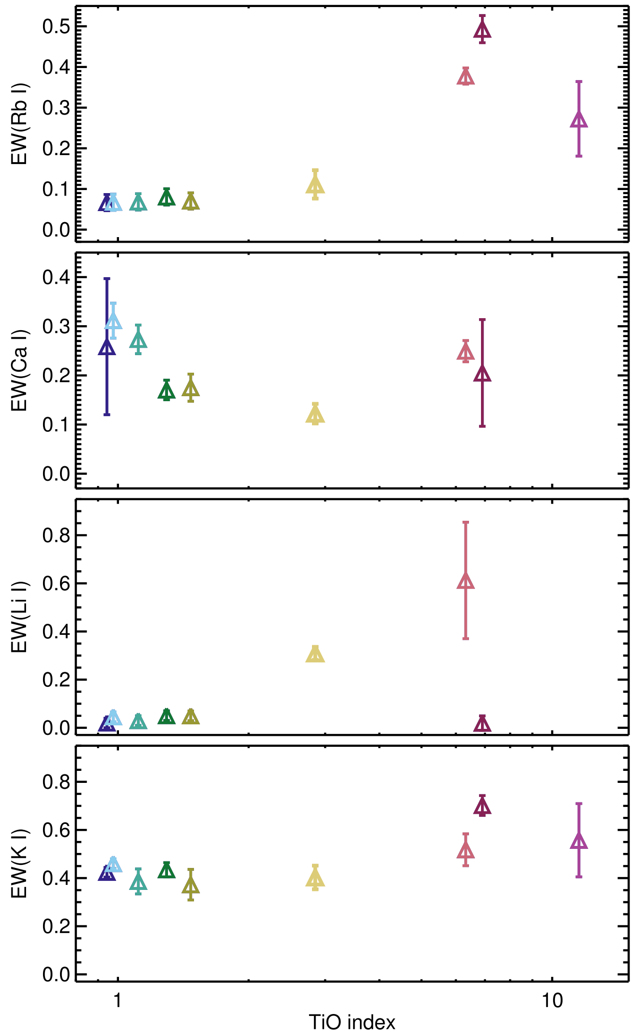

Figure 2. Pseudo-equivalent widths (pEWs) of the four spectral lines studied in L14, as a function of TiO absorption index. HV 2112 is denoted by the yellow triangle. For the star HV 12149 (the star with the highest TiO index), reliable measurements of the Ca I and Li I lines could not be made due to the low signal-to-noise of the spectrum at those wavelengths.

overabundance in Ca is difficult to explain with either the TŻO or AGB scenario.

In this paper we re-evaluate the above evidence in support of the TŻO classification for HV 2112. In the following section we discuss the surface abundances of HV 2112, by comparing the star's spectrum to other late-type SMC stars, and the effective temperature of the star, and we re-appraise the luminosity of HV 2112 using archival data.

2 A RE-EVALUATION OF THE EVIDENCE

2.1 Chemical abundances

It is predicted that TŻOs would have unusual abundance patterns due to the extreme temperatures at the surface of the NS, showing enhancement in a number of heavy elements due to the *irp*-process (e.g. Li I, Rb I, Mo I, Biehle 1991; Cannon 1993; Podsiadlowski et al. 1995). It was claimed in L14 that HV 2112 displayed over-abundances in Rb I, Mo I, Li I, and Ca I. These conclusions were not based on quantitative abundance analysis using model atmospheres. Instead, they determined pseudo equivalent widths[2] of various diagnostic lines, and compared certain line ratios to those of a sample of RSGs in the SMC. Any line ratio for HV 2112 that lay outside the 3σ limit of the comparison sample was considered to be indicative of an anomalous abundance ratio.

From the results presented in their fig. 1, L14 argue for an overabundance of rubidium (from the Rb I $\lambda\lambda$7800.23 / Ni I $\lambda\lambda$6707.97 ratio), lithium (from the Li I $\lambda\lambda$6707.97/Ca I $\lambda\lambda$6572.78 and Li I $\lambda\lambda$6707.97/K I $\lambda\lambda$7698.97 ratios), calcium (from the Ca I $\lambda\lambda$6572.78/Fe I $\lambda\lambda$7802.47 ratio), and molybdenum (from the Mo I $\lambda\lambda$5570.40/Fe I $\lambda\lambda$5569.62 ratio). However, attributing these line ratios to the abundance of the elements poses some problems. First, the Rb/Ni ratio suggests an *over*abundance of Rb, while the Rb/Fe ratio is normal. However, from the same figure the Ni/Fe ratio also appears to be within the normal 3σ range. If we attribute these line ratios directly to abundance ratios, it is not possible to find a self-consistent explanation. There is a similar problem for Li, Ca, and K. The Li/Ca and Li/K ratios could be interpreted as an overabundance in Li, while the Ca/Fe ratio appears to suggest an overabundance in Ca. However, the K/Ca ratio implies no overabundance in Ca, and appears normal.

Though we cannot explain the line strength ratios, it could be due to L14's comparison stars having very different temperatures and log(g) values, and it is likely that the lines in question are sensitive to such factors. There is also the issue that these lines are heavily blanketed by TiO, which is highly sensitive to $T_{\rm eff}$ and atmospheric structure (see Section 2.2). For these reasons we argue that it is not possible to draw conclusions about the abundances of the heavy elements from the L14 analysis alone.

2.1.1 *Comparative spectroscopy*

In this section, we attempt to circumvent the issues described in the previous section by comparing a spectrum of HV2112 to those of other stars in the SMC with similar luminosities and spectral types. To this end we have obtained an VLT+XSHOOTER spectrum of HV 2112 from the VLT archive (PI: C. Worley, ID: 096.D-0911(A)) as well as data from the X-Shooter Library (Chen et al. 2014).

[2] It is not possible to measure a strict equivalent width due to the high opacity in the optical spectra of cool stars. This is discussed further in Section 2.1.1.

Table 1. Comparison stars used in this work. Columns show the object name, co-ordinates, K-band magnitude from 2MASS, bolometric luminosity,[a] variability amplitude and period/time-scale for variability, waveband in which the variability was measured and the associated reference.

Name	RA Dec. (J2000)	K_S	$\log(L/L_\odot)$	Δm_λ	P (d)	λ	Ref.
SV* HV 1719	00 57 14.5−73 01 21.3	9.80	4.34	2.49	542	I	Soszynski et al. (2009)
SV* HV 12149	00 58 50.2−72 18 35.6	8.61	4.81	2.35	769	I	Soszynski et al. (2009)
PMMR 101	00 59 35.0−72 04 06.6	8.35	4.92	0.12	394	V	Groenewegen & Sloan (2018)
LHA 115-S 30	01 00 41.5−72 10 37.0	7.96	5.07	0.61	351	V	Watson, Henden & Price (2006)
SV* HV 11417	01 00 48.2−72 51 02.1	8.45	4.87	1.86	1092	I	Soszynski et al. (2009)
PMMR 127	01 01 54.2−71 52 18.7	8.69	4.78				
Cl* NGC 371 LE 29	01 03 02.5−72 01 53.1	8.62	4.81	0.84	543	I	Soszynski et al. (2009)
SV* HV 2112	01 10 03.9−72 36 52.6	8.72	4.70–4.91	1.27	603	I	Soszynski et al. (2009)
SV* HV 2232	01 30 34.0−73 18 41.7	8.60	4.82	0.47	506	V	Groenewegen & Sloan (2018)

[a]The luminosity here is calculated using K_S-band photometry and $BC_K = 3$ except for HV 2112 where the luminosity was determined using the method described in Section 2.3.

The sample of stars is listed in Table 1, along with their basic properties. The comparison stars were chosen for their late spectral types and SMC membership. Most are thought to be AGB stars from their moderately high luminosities ($\log(L/L_\odot) \gtrsim 4$), late spectral types and large amplitude photometric and spectroscopic variability (often $\gtrsim$1 mag in V over time-scales of 100s of days).

The optical spectral energy distributions (SEDs) of the stars are shown in Fig. 1. The spectra have been normalized to the apparently line-free spectral regions of HV 2112 to better illustrate the progression in absorption strengths with spectral type. To make a quantitative measurement analogous to spectral type we define the ‘TiO index’ to be the ratio of the fluxes either side of the TiO bandhead at 7020 Å.

In addition, for all stars in the sample we have measured the strengths of all lines studied by L14, specifically Rb I λ7800.23, Li I λ6707.97, Ca I λ6572.78, and K I λ7698.97. The high opacity in the optical spectra of cool stars prevents the measurement of a strict equivalent width since it is not possible to know where the true continuum is located. Instead we measured the pseudo-equivalent widths (pEWs), where the pseudo-continuum is defined to be the linear interpolation of flux-maxima either side of the line centre, similar to L14. We use Gaussian profile fitting to the absorption profile to determine the pEW of the spectral line, and we estimate uncertainties on pEW by moving the placement of pseudo-continuum blue/red by one pixel and remeasuring the line strength.

In Fig. 2 we plot the pEWs of each line studied as a function of the TiO index. HV 2112 is plotted as the large filled triangle. Though HV 2112 is somewhat of an outlier in terms of its spectral type when compared to typical RSGs in the SMC, the absorption in the lines of of Rb I, Ca I, and K I does not stand out as remarkable in comparison to the other late-type SMC stars. Indeed, they seem to be consistent with the very shallow trend with spectral type. The exception is the Li I line, where we see an apparent dichotomy of either effectively no Li absorption or a pEW $>$ 0.3 Å. Under the simple assumption that line strengths at a given spectral type reflect the abundance of the element, this suggests that HV 2112 may be Li-enriched. By contrast, we see no evidence for enhancement in any of the elements Rb, Ca, or K.

One star in our sample which does potentially show Rb enhancement is HV 11417, which can be seen in Fig. 2 as the star with the highest Rb I pEW. The star shows no evidence of Li enhancement, though the TiO bands are so strong in this star’s spectrum that they may completely overwhelm the Li I λ6707.97 line. Combined with its high luminosity ($\log(L/L_\odot) = 4.92$), we consider this star to be a TZO candidate until its Li abundance can be measured. Such a measurement may be possible when the star is in a phase of variability where it has an earlier spectral type and the Li I line is more clearly detectable.

2.2 Effective temperature

One key attribute of TŻOs is that they are expected to be cooler than the average RSG (Thorne & Żytkow 1977). To estimate the temperature of HV 2112, L14 fit MARCS stellar atmosphere models (Gustafsson et al. 2008) to the optical SED of HV 2112, deriving a $T_{\rm eff}$ of 3450 K. In fig. 3 of L14, it can be seen that there is a discrepancy between the spectrum of HV 2112 and the best-fitting MARCS model at near-UV and a near-infrared (near-IR) wavelengths (an excess and deficiency, respectively). The authors attribute this to circumstellar dust and strong mass-loss, also described in Levesque et al. (2005, 2006). It has also been argued that 3D model atmospheres produce greater TiO absorption at a given effective temperature in comparison to 1D models (Davies et al. 2013). Currently no models are capable of reproducing the whole spectrum of RSGs, though 3D hydrodynamical models show promise (Chiavassa et al. 2011). For this reason, we conservatively estimate the temperature of HV 2112 using Wien’s displacement law and the position of the flux peak, somewhere between I and J band. From this we estimate a temperature in the range of 2500–3750 K.

2.3 Luminosity

In L14, the luminosity of HV 2112 was estimated to be $\log(L/L_\odot) = 5.02$. This was calculated by correcting the V-band magnitude using the bolometric correction (BC) from Levesque et al. (2006), a distance modulus of 18.9 and an extinction of $A_V \sim 0.4$. However, as the BC is dependent on $T_{\rm eff}$ estimates from Levesque et al. (2006), which as previously discussed (see Section 2.2) may be overestimated, the BC itself may not be reliable.

A less model dependent method to estimate $L_{\rm bol}$ is to adopt the method described in Davies, Crowther & Beasor (2018), in which the SED is integrated under from the blue to the mid-IR. This method does not rely on uncertain BCs to determine $L_{\rm bol}$. Our only assumptions are that the emitted flux is spherically symmetric and any flux lost to circumstellar extinction in the optical is re-radiated at longer wavelengths.

We compiled photometry from OGLE (Udalski et al. 1992), ASAS (Pojmanski 1997), DENIS (Cioni et al. 2000), 2MASS

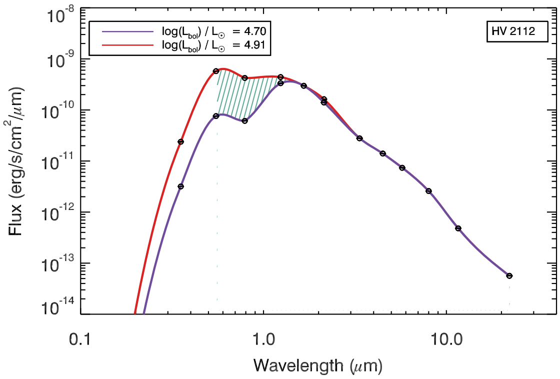

Figure 3. SED for HV 2112. The photometry is shown by black circles. The red line shows the flux at the peak of variability, while the purple line shows the flux at the minimum of variability, assuming the bolometric correction of the star does not change. The shaded green section shows the possible range of fluxes.

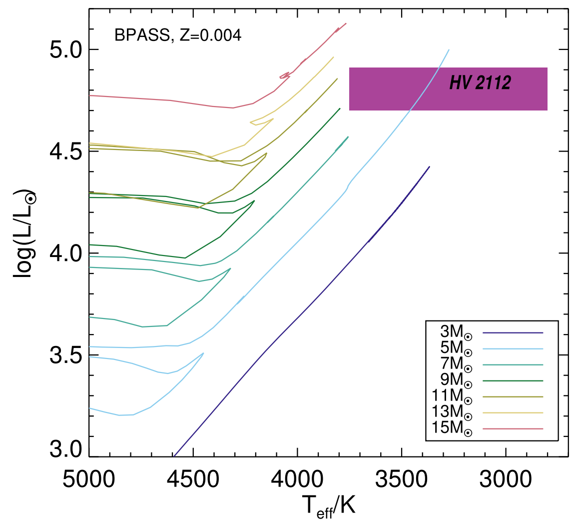

Figure 4. Position of HV 2112 on an HR diagram with BPASS models overplotted. The location of HV 2112 is consistent with that of a 5 $M_{\odot}$ star in the AGB phase.

(Skrutskie et al. 2006), *Spitzer* (Werner et al. 2004), and WISE (Wright et al. 2010). This photometry was de-reddened according to the SMC extinction law of Gordon et al. (2003) for an A_V value of 0.56 ± 0.26, found by interpolating the extinction maps of Zaritsky et al. (2002) to the position of HV 2112 (see Davies, Crowther & Beasor 2018). To account for any missing flux at short wavelengths, a black body spectrum of $T_{\rm eff} = 3000$ K was matched to the *B*-band flux.[3] We then integrated under the spectrum using `IDL` routine `int_tabulated` and corrected for the distance to the SMC.

One factor that might impact our determined $L_{\rm bol}$ is HV 2112's variability. The star is known to be a long period variable, and has been photometrically monitored by OGLE and ASAS. Specifically, HV 2112 is variable in *V* band by an amplitude of 2.2 mag (OGLE), *I* band by an amplitude of 2.1 mag (ASAS). In addition, HV 2112 has been observed twice by the DENIS survey, implying variability with an amplitude of at least 0.3 mag at *J* and of 0.13 mag at *K*. As these observations are not contemporaneous, we do not know how the colour evolves with the observed variability. It is therefore unclear if the variability is due to the star changing in $L_{\rm bol}$, $T_{\rm eff}$, or both. To find an upper and lower limit to HV 2112's luminosity during variability we will assume that BC does not change, see Fig. 3. By assuming the observed variability is due solely to changes in luminosity, we find a range of $\log(L/L_{\odot}) = 4.70$–4.91. The variability in luminosity is low, 0.21 dex, as despite the changing brightness at *V* and *I* bands most of the star's flux is emitted at $\lambda > 1$ μm, because of this the luminosity does not change by a large amount. The luminosity derived is also consistent with that derived by Smith et al. (1995), who found HV 2112 to have a luminosity of $\log(L/L_{\odot}) = 4.81$.

Fig. 4 shows the luminosity and temperature range for HV 2112 on a Hertzsprung–Russel diagram. We have overplotted stellar evolution models from BPASS (Eldridge & Stanway 2009) to demonstrate how the luminosity of a star changes with evolution. From these models, we cannot rule out an intermediate mass star ($\sim$5 $M_{\odot}$) in the AGB phase, as thermal pulses during this time are predicted to increase the luminosity to $\log(L/L_{\odot}) \sim 5$. This behaviour is also shown by MIST (Dotter 2016) and Padova (Salasnich, Bressan & Chiosi 1999) evolutionary tracks.

[3]The total luminosity contribution of this was small, approximately 0.02 dex. We also varied the effective temperature of the black body by $\pm$1000 K and it changed the value of luminosity by $\ll$0.01 dex.

3 DISCUSSION AND SUMMARY

We have re-examined the evidence for the TŻO candidate HV 2112. Below we summarize our results:

(i) We have compared archival spectra of HV 2112 to that of other SMC stars with similarly late spectral types. We find that the line strengths of K I, Ca I, and Rb I are normal with respect to the comparison stars, suggesting no evidence of enhancement of any of these elements. The only exception to this is Li which may be enriched.

(ii) Using archival photometry from 0.4 to 25 μm and integrating under the SED we find a bolometric luminosity for HV 2112 of $\log(L/L_{\odot}) = 4.72$, with an upper limit of $\log(L/L_{\odot}) = 4.91$. This limit comes from the star's variability under the conservative assumption that the bolometric correction does not change. This luminosity is lower than previously suggested, and is consistent with predictions for 5 $M_{\odot}$ AGB stars which can have luminosities of $\log(L/L_{\odot}) \gtrsim 5$ (e.g. Eldridge & Stanway 2009).

(iii) While the precise temperature of HV 2112 remains unknown, it is clear that it is a cool star ($T_{\rm eff} \sim 3000$ K).

Given the downward revision in luminosity and re-evaluation of the surface abundances in HV 2112, we argue that HV 2112 does not meet the criteria to be considered a TŻO candidate. Instead, it is likely a thermally pulsing AGB star.

However, we also identify another TŻO candidate in HV 11417. This object has a high luminosity ($\log(L/L_{\odot}) = 4.92$) and seemingly strong Rb I line. The star has a very late spectral type, so much so that the deep TiO absorption bands do not allow us to measure the strengths of the λ6707.97 Li line. We suggest that HV 11417 is a more promising candidate TŻO, pending a measurement of the Li abundance. Such a measurement could be made when the star is in an earlier spectral-type phase of its variability. Spectral monitoring may allow observations at an earlier spectral type, when the Li line could be seen.

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