HV2112, a Thorne–Żytkow Object or a Super Asymptotic Giant Branch Star

Christopher A. Tout\textsuperscript{1⋆}, Anna N. Żytkow\textsuperscript{1}, Ross P. Church\textsuperscript{2,1} and Herbert H. B. Lau\textsuperscript{3}

\textsuperscript{1}Institute of Astronomy, The Observatories, Madingley Road, Cambridge CB3 0HA
\textsuperscript{2}Department of Astronomy and Theoretical Physics, Lund Observatory, Box 43, SE–221 00, Lund, Sweden
\textsuperscript{3}Argelander Institute for Astronomy, University of Bonn, Auf dem Huegel 71, D-53121 Bonn, Germany

ABSTRACT

The very bright red star HV2112 in the Small Magellanic Cloud could be a massive Thorne–Żytkow Object, a supergiant-like star with a degenerate neutron core. With its luminosity of over $10^5 \, \text{L}_\odot$, it could also be a super asymptotic giant branch star, a star with an oxygen/neon core supported by electron degeneracy and undergoing thermal pulses with third dredge up. Both TZO\textsc{es} and SAGB stars are expected to be rare. Abundances of heavy elements in HV2112’s atmosphere, as observed to date, do not allow us to distinguish between the two possibilities based on the latest models. Molybdenum and rubidium can be enhanced by both the \textit{irp}-process in a TZO or by the \textit{s}-process in SAGB stars. Lithium can be generated by hot bottom burning at the base of the convective envelope in either. HV2112’s enhanced calcium could thus be the key determinant. A SAGB star is not able to synthesise its own calcium but it may be possible to produce this in the final stages of the process that forms a TZO, when the degenerate electron core of a giant star is tidally disrupted by a neutron star. Hence our calculations indicate that HV2112 is most likely a genuine TZO.

Key words: stars: AGB and post-AGB – stars: abundances – binaries: close – stars: evolution – stars: individual: HV2112

1 INTRODUCTION

Observations by Levesque et al. (2014) of the very bright red star HV2112 in the Small Magellanic Cloud (SMC) suggest that it could be a Thorne–Żytkow object (TZO). Thorne & Żytkow (1975, 1977) first modelled these stars with neutron-star cores and a structure somewhat resembling that of a red supergiant. Levesque et al. (2013) demonstrate that HV2112 is spectrally very different from other red supergiants in the SMC. It has noticeably enhanced spectral features corresponding to rubidium and molybdenum, which were predicted to show up in massive TZO\textsc{es} (Biehle [1991, 1994]; Cannon [1993]) as well as lithium (Podsiadlowski et al. [1995]). It is not certain how these objects are formed. Thorne & Żytkow (1975, 1977) originally proposed either a failed supernova or a neutron star accreting in a binary system. In the former case there is insufficient energy released to expel a very massive envelope when a degenerate core collapses to a neutron star. This is expected in the deaths of very massive stars (Eldridge & Tout [2004]) but it is generally thought that fallback on to the neutron star converts it to a black hole. In the binary mechanism the neutron star is formed in a normal supernova of the originally more massive component in a close binary system. The mass loss and any kick are insufficient to unbind the system. Subsequently its companion evolves to a giant and fills its Roche lobe. It is then the more massive of the two objects and has a deep convective envelope. Mass transfer proceeds rapidly on a time-scale approaching dynamical. The core of the giant and the neutron star are together both smothered by the giant’s envelope and spiral inwards to merge. The last phase of the merge occurs once the cores have spiralled close enough together that the electron degenerate core is tidally disrupted and forms an accretion disc in the orbital plane of the binary deep inside the envelope. This occurs on a very short time-scale and leaves a neutron star at the centre of the giant common envelope. This configuration settles to become the TZO.

Though the spectrum observed by Levesque et al. (2014) differs significantly from the other red supergiants

⋆ email: cat@ast.cam.ac.uk

© RAS
they looked at in the SMC they do not explicitly discuss super asymptotic giant branch (SAGB) stars. These are the late stages of stars of initial mass in a range of a few solar masses somewhere between about 6 and 12 $M_\odot$, depending upon assumptions made about convective overshooting during core helium burning, that have gone on to ignite carbon in their cores before the second dredge up (García-Berro & Iben 1994). In general, stars of intermediate mass evolve through core hydrogen 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 of the products of hydrogen burning to the surface. Once hot enough, helium burning led by the triple-$\alpha$ process ignites in the core which burns convectively to carbon and oxygen. After its exhaustion in the core helium burns out in a shell following the hydrogen burning shell. These double shell burning stars are on the asymptotic giant branch (AGB). In the more massive AGB stars, a second dredge up takes place when the deep convective envelope penetrates beyond the temporar-ily extinct hydrogen burning shell. This brings new hydrogen fuel to reignite the hydrogen shell only a few hundredths of a solar mass outside the helium burning shell. The thin extent of the helium-rich region, coupled with the strong temperature sensitivity of the triple-$\alpha$ reaction, causes unstable helium burning in pulses between which episodes of third dredge up bring the products of helium burning to the surface. Amongst these are slow neutron capture isotopes (Karakas & Lattanzio 2014) that can account for the heavier than iron elements observed in HV2112. The higher mass SAGB stars ignite carbon before the second dredge up but go on to thermally pulse and dredge up in a similar way. They have higher core masses at second dredge up and it is this that gives them luminosities as high as red supergiants and TZO early on. Once thermal pulsing and third dredge up has begun, the core, and hence luminosity, grow much more slowly.

In the subsequent sections we look carefully at the various properties of HV2112. In almost all cases these are explained straightforwardly by both SAGB stars and TZO. The major exception is the enhanced calcium. Neither SAGB stars nor TZO can make calcium. Its production by very hot burning may be due to more extreme processes involved in the formation of a TZO.

## 2 LUMINOSITY AND TEMPERATURE

The bolometric luminosity of HV2112 is estimated to be $10^{4.15-15} L_\odot$. The structure of a red giant envelope depends on the luminosity generated deep with its core and its opacity which determines its Hayashi track (Hayashi & Hoshi 1961). Both TZO (Cannon 1993) and SAGB stars (Smartt et al. 2002, Doherty et al. 2014) can reach the required luminosity. Because their structures, dense degenerate cores and deep convective envelopes, are rather similar they appear at similar locations in the Hertzsprung-Russell diagram. In both cases their luminosity is generated primarily by nuclear burning around their compact degenerate cores. Because both sorts of star lie on a Hayashi track their temperature is almost entirely determined by their luminosity with only a slight dependence on their total mass. Normal AGB stars can also reach these luminosities towards the end of their lives but by then they are rich in heavy s-process elements such as barium, and have destroyed all their lithium, inconsistent with HV2112 as we discuss below.

## 3 PROBABILITIES

Neither SAGB stars nor TZO are common. We make an order of magnitude estimate of the number that should be expected in the SMC. Doherty et al. (2010) find that, at SMC metallicity, SAGB stars form at masses between 6.5 and 8 $M_\odot$. By a simple integration of the Kroupa, Tout & Gilmore (1993) mass function this implies that one SAGB progenitor should form per 453 $M_\odot$ of total star formation. The SAGB stage lasts for a few $10^5$ yr while the total lifetimes of the progenitors are a few $10^8$ yr (Doherty et al. 2010, 2014). Hence roughly one out of every thousand stars of the correct mass should be a SAGB star at any given time. From fig. 5 of Glatt et al. (2010) we obtain that there are roughly 250 stellar clusters with ages around 300 Myr, and their fig. 13 suggests a mean mass of perhaps 4000 $M_\odot$, giving a total mass of about $10^8$ $M_\odot$ in clusters that could host SAGB stars. Putting these numbers together suggests that the total number of SAGB stars in the SMC at the current time should be of order unity. Within the accuracy of this calculation this would be consistent with HV2112 being the only SAGB star found in the SMC so far.

To compare the expected number of SAGBs with TZO we have used the binary star population synthesis algorithm BSE (Hurley et al. 2002) to synthesise a population of binary stars. We give all stars above 8 $M_\odot$ companions, with masses chosen to be uniformly distributed in mass ratio $q$, and distribute the initial semi-major axes uniformly in $\log a$ with $q$ between 10 and $10^4$ $R_\odot$. These are optimistic assumptions because we neglect non-interacting wider binaries and any single massive stars. We find that two per cent of our binaries form a TZO, equivalent to one TZO per 453 $M_\odot$ of total star formation. The progenitor lifetimes prior to TZO formation are typically of order 10 Myr. If we assume that the lifetimes of the TZO are limited by strong winds driven by Mira-like pulsations with mass-loss rates similar to the superwinds of AGB stars (Vassiliadis & Wood 1993) then the lifetimes of the TZO are about 10 yr. So again roughly one out of every thousand should be visible. Taking there to be very roughly $10^6$ $M_\odot$ in clusters of ages around $10^6$ yr one would then expect a probability of there being a TZO visible in the SMC at the current time of about ten per cent. This number is in approximate agreement with the calculation of Podsiadlowski et al. (1993) given the mass ratio of the SMC to the Milky Way. However, the rate of TZO formation depends very strongly on the assumptions made about the efficiency with which the envelope of the giant is removed by the spiralling in process. Here we assume that all the energy liberated from the orbit goes into unbinding the envelope with no additional energy, such as recombination of atoms, liberated. Making different, reasonable, assumptions we can easily change the formation rate by an order of magnitude. Hence it is not possible to draw any strong conclusions about the likelihood of HV2112 being a TZO from predicted formation rates alone.
It is also possible that TŻOs could be formed in the core-collapse of the most massive single stars, above say 24\,M\odot, if the energy released is insufficient to eject all of the envelope. In this case there is no supernova explosion. A simple calculation, analogous to that for SAGB stars above, suggests that the resulting objects should be roughly equally as common as SAGB stars. If a sufficient fraction of the material that has reached very high temperatures during the core collapse can avoid being incorporated into the compact object, this could potentially also produce the observed calcium abundance. It has always been assumed that, in this scenario, material falling back on to the newly-formed neutron star would convert it into a black hole. This would destroy the star on a short time-scale and prevent the irp-process from taking place. However if black hole formation can be avoided this mechanism would provide roughly as many TŻOs as SAGB stars whilst allowing them to be rich in calcium.

4 HEAVY ELEMENTS

HV2112 is rich in rubidium and molybdenum. These can be produced by the irp-process in TŻOs (Cannon 1993). They can also be produced by the s-process in SAGB stars (Doherty, private communication; Lau et al. 2011). The s-process begins with neutron captures on to iron-group nuclei. Initially lighter elements are built up and both rubidium and molybdenum are members of this light s-process set. Subsequently, depending on the degree of neutron exposure, heavier elements including barium and eventually lead are formed. Levesque et al. (2014) found barium not to be enhanced in HV2112 and claimed that this is evidence that the s-process is not responsible for the rubidium and molybdenum.

The s-process nucleosynthesis of SAGB stars is still rather uncertain. Lau et al. (2011) compute yields for 8, 8.5 and 9\,M\odot stars of solar metallicity. They find significant enhancements in the light s-process elements consistent with neutrons produced by the 22Ne(α,γ)25Mg reaction. The yields, defined as the ratio of the average abundances in the stellar wind to those in the star initially, are between a factor of 100–5 and 10. The enhancement in strong s-process isotopes, however, depends very strongly on the rates of the triple-alpha and 12C(α,γ)16O reactions, which control the temperature at the base of the intershell convective zone. Lower, older rates led to very little heavy s-process, while newer, faster rates produce significant quantities. In light of this result and in the absence of a more detailed analysis we consider that the abundance trends in rubidium and molybdenum are consistent with in-situ production by an SAGB star.

We note that, in general, a simple test for ongoing s-process activity is to look for technetium in the atmosphere of the star. However technetium is also expected to be produced by the irp-process. The models of Cannon (1993) show Tc number abundances between 10^{-9} and 10^{-6}, which are comparable to or higher than some of the more Tc-enhanced S-star abundances (e.g. Abia & Wallerstein 1998). It is in general rather difficult to obtain accurate abundances for Tc because its spectral lines are blended with those from other elements.

5 LITHIUM

Lithium is produced during hot bottom burning in the early phases of AGB and SAGB evolution by the Cameron (1953) mechanism. The typical temperatures at the base of the convective envelopes of SAGB stars after second dredge-up are above 60\,MK which allows hot-bottom burning and the synthesis of lithium. First 7Be is produced by the reaction

\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]  

(1)

and this captures an electron to form 7Li,

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu. \]  

(2)

Some lithium produced by hot-bottom burning may be transported to the surface by convection so there is a short period of time in which Li is significantly enhanced, in many models by more than a factor of ten, at the surface. Lithium that is mixed back to or remains in the hot burning region is subsequently destroyed by proton capture

\[ ^7\text{Li} + ^1\text{H} \rightarrow ^2^4\text{He}. \]  

(3)

Furthermore, the production of lithium ceases when 3He is depleted, so the surface abundance of lithium decreases after its initial peak during the early AGB or SAGB phase.

Because lithium is significantly enhanced before any thermal pulses, the surface composition of an SAGB star is rich in lithium before it is enhanced in s-process isotopes. In fact, we expect stars with observed strong Li enhancements not yet to be enhanced in s-process isotopes, for example R Nor with A(Li) = 4.6 (Uttenthaler et al. 2011). However, while we do not expect to observe SAGB or AGB stars with simultaneously strong Li and s-process enhancement, the surfaces of early thermally pulsing SAGB or AGB stars can have mild Li and s-process enhancement at the same time. During the first few pulses, light s-process isotopes are dredged up to the surface while most lithium previously produced begins to be destroyed. Depending on the initial mass and treatment of convection, this period of mild Li and s-process enhancement lasts about 10^3–10^6\,yr (see fig. 3 of Doherty et al. 2014). van Raai et al. (2012) find that the Li-rich phase lasts for 10^5\,yr in a 6\,M\odot model. Their fig. 7 shows that Li and Rb can be enhanced at the same time.

Thorne-Żytkow objects also synthesise lithium by the same mechanism, the hot region in this case is the base of the convective envelope just above the degenerate core. Podsiadlowski et al. (1995) find that, for a typical example model, the lithium abundance increases for the first 10^6\,yr and is still enhanced after 10^6\,yr, the maximum lifetime they consider possible. Therefore there is no problem with simultaneously obtaining rubidium, molybdenum and lithium in a TŻO.

6 CALCIUM

Levesque et al. (2014) find enhanced calcium in HV2112. Calcium is produced by the capture of alpha particles during the final stages of a star’s nuclear lifetime when photodisintegration and alpha captures convert silicon-28 to nickel-56 immediately before a supernova explosion. It is not enhanced by ongoing nucleosynthesis in either TŻOs or SAGB stars. At no point in its earlier life has an SAGB star reached the
necessary conditions to synthesise calcium anywhere in its interior and so cannot account for this excess calcium which could then only be explained by fortuitous external pollution. A TZO has however more potential because its neutron star core was likely produced by the collapse of a degenerate iron-rich core that exceeded the Chandrasekhar mass.

The total mass of calcium in the Sun, nearly all $^{40}$Ca, is about $6 \times 10^{-5} M_\odot$. The metallicity of the SMC is about a tenth that of the Sun so if we imagine we need to enhance calcium in the an envelope of say $10 M_\odot$ or so by a factor of three we require about $10^{-4} M_\odot$ to mix through the whole envelope.

Typical type-II supernovae expel between about $10^{-3}$ and $2 \times 10^{-2} M_\odot$ of $^{40}$Ca (Woosley & Weaver 1995) which is up to one hundred times what is needed to pollute our typical TZO envelope. Unfortunately ejecta of supernovae leave at over 1,000 km s$^{-1}$ so that only material directly impacting the companion can be accreted. For a separation $a$ and companion radius $R$ the fraction accreted may be estimated as

$$f \approx 4 \times 10^{-4} \left( \frac{R}{5 R_\odot} \right)^2 \left( \frac{\text{AU}}{a} \right)^2.$$ 

Typical progenitors of type-II supernovae are red supergiants with radii approaching $1000 R_\odot$ (Smartt 2009). To fit such a supergiant into an orbit with our star would require $a > 10$ AU which means that the fraction of material accreted would be too small even if our star is already a giant at that stage.

Another possibility is that the calcium could have been synthesised during the formation of the TZO. When the degenerate core merges with the neutron star the conditions in the accretion disc are appropriate for advanced burning and calcium production. Metzger (2012) has computed the nucleosynthesis expected during the accretion of the disc produced by a disrupted white dwarf. He finds that for a 0.6 $M_\odot$ white dwarf, which is the most similar of his models to the cores of the massive giant companions that we are considering, around $10^{-3}$ $M_\odot$ of calcium should escape from the disc. This exceeds the mass required to pollute the envelope to the extent necessary to produce the surface enhancement of Ca observed in HV2112. However material in the disc either accretes directly on to the neutron star or is expelled in a high-velocity outflow. The velocity of this wind from the accretion disc must be roughly equal to the escape velocity at a distance equal to the characteristic length scale of the disc. Because the disc is somewhat smaller than the white dwarf radius this velocity exceeds $10^8$ km s$^{-1}$. Naively comparing the kinetic energy in this outflow with the binding energy of the envelope shows that there is enough energy available to completely unbind the star, leaving a naked neutron star. However, evidence from other objects with relativistic outflows, including gamma-ray bursts, active galactic nuclei and X-ray binaries, he suggests that collimated outflows (jets) are common, if not ubiquitous, in such systems. Duffell & MacFadyen (2013) find that for a GRB jet, somewhat comparable to what we expect for a merging WD–NS system, Kelvin–Helmholtz instabilities along the boundaries of these jets can mix as much as a tenth of the material with the envelope they are punching through.

Hence we postulate that the wind from the central accretion flow was rather collimated. In the process of blowing a chimney through the star convective motions around the boundaries of the flow mixed some fraction of the wind – at least a tenth of its mass – into the envelope of the supergiant. The rest of the wind was lost along the polar axis of the disc, taking the kinetic energy with it. This picture is roughly consistent with what we see in other systems that posses a relativistic accretion disc and accounts for the calcium enrichment.

We note also that in Metzger’s models only a small fraction of the white dwarf – typically about one tenth – is accreted on to the neutron star. This is sufficiently little that it is possible for a stable neutron star to continue as the central object rather than necessitating a collapse to a black hole. Because his method does not permit him to follow burning that occurs whilst the disc is forming he does not consider discs formed by the disruption of more massive white dwarfs by neutron stars. Such models might be more appropriate for the cores of the relatively massive companion that we postulate here. Since they would be more massive and denser they would most likely produce a greater quantity of calcium, reducing the fraction of the synthesised material which we require the envelope to absorb.

7 CONCLUSIONS
We have analysed the possibilities that the unusual SMC supergiant, HV2112, is either a super-AGB star or a Thorne–Zytkow object. Whilst the formation probabilities are only very slightly in favour of an SAGB star, the uncertainties in the formation rates are such as to make this argument very weak. We find that the majority of HV2112’s observed properties are consistent with either possibility. The observed luminosity and temperature are both within those expected. Both classes of objects are expected to synthesise lithium, rubidium and molybdenum in situ. The most distinguishing feature is the high observed calcium abundance. This calcium cannot be produced by the $s$-process, nor can it be accreted directly on to the surface of HV2112 by the supernova explosion of a binary companion. We propose that the calcium could be produced by nuclear burning in the degenerate core of the companion giant as it merges with a neutron star to form the Thorne–Zytkow object. The observation of enhanced calcium thus suggests that HV2112 is most likely a genuine Thorne–Zytkow object and that it has probably formed from the merging of a binary star progenitor.

ACKNOWLEDGEMENTS
The authors would like to thank Carolyn Doherty and Robert Izzard for useful discussions. CAT thanks Churchill College Cambridge for his fellowship. RPC is supported by the Swedish Research Council (grants 2012-2254 and 2012-5807) and would like to thank the Institute of Astronomy, Cambridge for their hospitality during his visit.

REFERENCES
Abia C. & Wallerstein G, 1998, MNRAS, 293, 89
Biehle G. T., 1991, ApJ, 380, 167
Biehle G. T., 1994, ApJ, 420, 364
HV2112, a TZO or a SAGB star

Cameron A. G. W., 1955, ApJ, 121, 144
Cannon R. C., 1993, MNRAS, 263, 817
Doherty C. L., Gil-Pons P., Lau H. H. B., Lattanzio J. C., Siess L., 2014, MNRAS, 437, 195
Doherty C. L., Siess L., Lattanzio J. C., Gil-Pons, P., 2010, MNRAS, 401, 1453
Duffell, P. C., MacFadyen, A. I., 2013, ApJ, 775, 87
Eldridge J. J, Tout C. A., 2004, MNRAS, 348, 201
García-Berro E., Iben I., 1994, ApJ, 434, 306
Glatt K., Grebel E. K., Koch A, 2010, A&A, 517, 50
Hayashi C., Hoshi R., 1961, 13, 442
Hurley J. R., Tout C. A., Pols, O. R., 2002, MNRAS, 329, 897
Karakas A. I., Lattanzio J. L., PASA, in press
Kroupa P., Tout C. A., Gilmore G., 1993, MNRAS, 262, 545
Lau H. H. B., Dougherty C. L., Gil-Pons P., Lattanzio J. C., 2012, Mem. Soc. Astron. Italy Suppl., 22, 247
Lau H. H. B., Dougherty C. L., Gil-Pons P., Lattanzio J. C., 2011, in Kerschbaum F., Lebzelter T., Wing R. F., eds, ASP Conf. Ser. Vol. 445, Why Galaxies care about AGB Stars II: Shining Examples and Common Inhabitants. Astron. Soc. Pac. San Francisco, p 45
Levesque E. M., Massey P., Zytkowski A. N., Morrell N., 2014, MNRAS, in print
Metzger B. D., 2012, MNRAS, 419, 827
Podsiadlowski P., Cannon R. C., Rees M. J., 1995, MNRAS, 274, 485
Smarrt S. J., Gilmore G. F., Tout C. A., Hodgkin S. T., 2002, ApJ, 565, 1089
Smarrt S. J., 2009, ARA&A, 47, 63
van Raai M. A., Lugano M., Karakas A. I., García-Hernández D. A., and Yong D., 2012, A&A, 540, A44
Thorne K. S., Zytkowski A. N., 1977, ApJ, 212, 832
Thorne K. S., Zytkowski A. N., 1975, ApJ, 199, 19L
Uttenthaler S. et al., 2011, A&A, 531, 88
Vassiliadis E., Wood P. R., 1993, ApJ, 413, 641
Woosley S. E., Weaver T. A., 1995, ApJS, 101, 181