Is the central binary system of the planetary nebula Henize 2–428 a Type Ia supernova progenitor?

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ABSTRACT

We account for recent observations of the binary system at the center of the bipolar planetary nebula Henize 2–428 by the presence of one degenerate core with a low-mass main sequence companion, rather than by two degenerate objects. We argue that the variability of the He II 5412 Å spectral line can be accounted for by a time-varying broad absorption line from the central star on top of which there is a time-varying narrow emission line from the compact nebula. The two (almost) symmetric broad minima in the light curve are attributed to tidal distortion caused by a companion. We find problems in the recently proposed and competing explanation of two equal-mass degenerate objects that supposedly will eventually merge, possibly leading to a SN Ia. We conclude that Henize 2–428 cannot be claimed yet to support the double-degenerate scenario for Type Ia supernovae.

Key words: supernovae: general — planetary nebulae — white dwarfs

1 INTRODUCTION

Thermonuclear, or Type Ia supernovae (SNe Ia), are the result of the explosion of carbon-oxygen white dwarfs. Despite their well known observed properties, the nature of the progenitor systems which produces a SNe Ia event has not been hitherto elucidated, and several scenarios have been proposed, none of which gives a satisfactory answer to all the abundant observational material. The scenarios can be classified into six categories — see, for instance, Tsebrenko & Soker (2013) for a recent discussion of some of the categories, and Wang & Han (2012) and Maoz et al. (2014) for extended reviews of some of these scenarios.

As there is no consensus on which are the SN Ia progenitor(s), it is crucial to refer to all scenarios (or categories of scenarios) when confronting them with observations. We list them in alphabetical order, and cite only a few references for each scenario: a) The core-degenerate (CD) scenario (Livio & Riecci 2002; Kashi & Soker 2011; Soker et al. 2013), b) The double-degenerate (DD) scenario (e.g., Webbink 1984; Iben & Tutukov 1984), c) The double-detonation (DDet) mechanism (e.g., Woosley & Weaver 1994; Livne & Arnett 1995; Shen et al. 2013), d) The single-degenerate (SD) scenario (e.g., Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004), e) The recently proposed singly-evolved star (SES) scenario (Chiosi et al. 2014), and f) The WD-WD collision (WWC) scenario (e.g., Raskin et al. 2004; Thompson 2014; Kushnir et al. 2014; Aznar-Siguán et al. 2013).

Since all these scenarios involve white dwarfs, all progenitors evolve through one or two planetary nebula (PN) phases. Accordingly, one of the pieces of evidence that would help in constraining SN Ia scenarios is to study PNe. For instance, in some cases SN Ia have been even claimed to take place inside planetary nebulae (e.g., Dickel & Jones 1985; Tsebrenko & Soker 2013, 2015), a process termed SNIP.

In a recent paper Santander-Garcia et al. (2013) analyze the central binary system of the planetary nebula Henize 2–428 (Rodríguez et al. 2001; Santander-Garcia et al. 2011). Santander-Garcia et al. (2013) find that the light curve of this PN shows two nearly identical broad minima, and that there is an absorption line of He II 5412 Å that varies with time. Given that the two minima of the light curve are practically the same, they assume that these are caused by a binary system composed of two equal-mass stars of the same type, and find the temperature, radius, and luminosity, of the two stars to be almost identical. They further argue that most likely these are two degenerate stars, i.e., white dwarfs or cores of post-asymptotic giant branch (AGB) stars, on their way to become CO white dwarfs. As the combined mass in this
model is $1.76M_\odot$, Santander-Garcia et al. (2013) further argue that these two stars will merge to form a SN 1a in the frame of the DD scenario.

As we explain in section 2, we find the interpretation by Santander-Garcia et al. (2013) to be very unlikely. Instead, in section 3 we propose a binary model with only one degenerate star. Our short summary is in section 4.

2 A CRITICAL ANALYSIS OF THE OBSERVATIONS

2.1 A binary system made of two identical stars?

Santander-Garcia et al. (2013) argue for a binary system composed of two stars having the same mass, $0.88\pm0.13M_\odot$, the same luminosity, $\approx 420L_\odot$ at a distance of 1.4 kpc, and the same radius, $0.68\pm0.04R_\odot$. This implies that the two stars are at the same evolutionary stage. However, any small difference in the main sequence mass will turn to a large one on the asymptotic giant branch (AGB). An AGB star having a core of $0.88M_\odot$ burns hydrogen at a rate of $\sim 2\times10^{-7}M_\odot$ yr$^{-1}$ (e.g., Paczynski 1970). For a difference in mass between the two cores of $<0.02M_\odot$ the initial time difference between the evolving stars should be $\lesssim 10^3$ yr. This requires a mass difference on the main sequence of $\Delta M/M \lesssim 10^{-3}$, depending on the initial mass of the stars. Such a case is possible, but rare, hence motivates us for a careful reexamination of such a claim.

2.2 Stellar properties

As mentioned, in the model proposed by Santander-Garcia et al. (2013) each star is a post-AGB star with a mass of $0.88M_\odot$. When a post-AGB of that mass fades to a luminosity of $\approx 1000L_\odot$, its radius is already $\approx 0.02R_\odot$ (e.g., Biocini & Schonenberger 1991). This radius is about 30 times smaller than the radius suggested by Santander-Garcia et al. (2013).

We instead propose that the luminosity of the system is due to just one star, and the luminosity of the companion is negligible. At a distance of $D = 1.4$ kpc as deduced by Santander-Garcia et al. (2013) the luminosity is $\approx 850L_\odot$. This can be a star whose evolution was truncated on the upper red giant branch (RGB), when its core mass was only $M_1 \approx 0.45M_\odot$, or on the lower AGB when its core mass was $\approx 0.5M_\odot$. On the other hand, if the distance is larger, say $D = 1.8$ kpc, the luminosity is $\approx 1,400L_\odot$. This can be a star whose evolution was truncated on the lower AGB, when its core mass was only $M_1 \approx 0.52-0.55M_\odot$. In our proposed model the companion that terminated the RGB or the AGB evolution is a main sequence star of $\sim 0.3-0.5M_\odot$.

A note is in place here on the distance to Henize 2-428. Santander-Garcia et al. (2013) provide a rough estimate of the distance of $1.4 \pm 0.4$ kpc based on the dereddened apparent magnitudes of Henize 2-428. Maciel (1984) obtained a distance of 1.7 kpc, whereas Cahn & Kaler (1971) derived a distance of 2.7 kpc. Based on these three values we will scale our expressions with two distances, $D = 1.4$ kpc and $D = 1.8$ kpc.

2.3 An alternative explanation of the spectral features

The strongest argument of Santander-Garcia et al. (2013) for their claim of a binary system of equal-mass stars is the line profile of the He II 5412 Å line, and the nearly identical minima in the light curve — see their Figs. 2 and 3. These properties have been suggested to be indicative that both members of the binary system have very similar masses. By fitting the line profile with Gaussian profiles they concluded that the two stars show Doppler shifts compatible with a system made of equal-mass stars, and in their joint analysis of the light curve and the spectrum forced the mass ratio $q = M_2/M_1$ of the binary system to be 1. This is a critical assumption of their analysis, and it is motivated by the presence of two nearly identical minima in the light curve.

We inspected the line profile as given in figure 3 of Santander-Garcia et al. (2013). There are three properties that do not comply with the Doppler shifts of two equal-mass stars. (i) The two minima do not always vary in a symmetrical way. For example, from panel a to panel b of their figure 3. While the red-shifted (right) minimum moves to higher velocities, the blue-shifted one only becomes shallower. (ii) The main difference between panel a and panel d is that the spectral feature between the two minima in panel d is lower and blue-shifted relative to that in panel a. (iii) The prominent spectral feature (the peak between the two troughs) in panel a is very narrow and sharp. Two Gaussian absorption profiles to its two sides would have difficulties in explaining it.

Overall, it seems that the main changes between the different panels of figure 3 as presented by Santander-Garcia et al. (2013) are intensity variations. We therefore suggest that the line profile is the result of a wide absorption line belonging to the primary star, and a narrow emission line coming from the compact dense nebula reported by Rodríguez et al. (2001), or even much closer to the star from the wind itself. Both emission and absorption lines change with orbital phase. Many central stars of planetary nebulae show He II absorption lines (e.g., Weidmann & Gamen 2011). The emission line is seen in some nebulae, e.g., in Abell 48 whose central star is a WN star (Todt et al. 2013). Most interesting in the study of Weidmann & Gamen (2011) are several PNe that show a wide He II 5412 Å absorption line with a weak emission feature in the center of the wide absorption line. This forms a double-trough structure similar to that of Henize 2-428. The most noticeable examples of this are the PNe He 2-105, He 2-434, and to some degree SP 3 and PC 12. All these central stars are O stars.

To these we add the PN Pa 5, for which the central star shows a wide He II 5412 Å absorption line and the resolved nebula shows a narrow He II 5412 Å emission line (García-Díaz et al. 2014). The minimum in the broad absorption line is $4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ below the continuum, and the total absorbed flux is $10^{-15}$ erg s$^{-1}$ cm$^{-2}$. The emission line is very narrow, and its peak is $2 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ above the continuum whereas the emission flux is $3 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. The conclusion is that a narrow He II 5412 Å emission line can fill a substantial fraction of the absorption line. This is our pro-
posed explanation for the double-trough structure reported by Santander-Garcia et al. (2015) for Henize 2–428.

It could be argued that if our interpretation is correct, and the He II 5412 Å emission line is nebular, a He II 4686 Å emission line should be also observed; but it is not. However, other PNe, like He 2–105, PC 12, He 2–34 and SP 3 have spectra with weak He II 5412 Å bumps (which we interpret as an emission line) in the center of a broad absorption line, whereas the He II 4686 Å line is in absorption (Weidmann & Gamer 2011). On the other hand, in the planetary nebula M 1–14 the He II 5412 Å line is in absorption but the He II 4686 Å occurs in emission (Weidmann & Gamer 2011). These cases show that there is an interplay between emission and absorption in the He II lines. This suggests that the emission, like the absorption, originates very close to the star, but not at the same place. Both absorption and emission vary with orbital phase.

Our model allows us to relax the constraint on the effective temperature of the central star set by Santander-Garcia et al. (2015). Based on the absence of He II 5412 Å line they established an upper limit on the effective temperature of the members of the binary system of ≈ 40,000 K. If our interpretation of this spectral feature is correct, and an emission line does exist, then this upper limit to the effective temperature would no longer be valid, and the effective temperature should be sufficiently large to allow emission. Below we will scale quantities with an effective temperature of $T_{\text{eff}} = 45,000$ K.

3 THE PROPOSED BINARY MODEL

3.1 Present binary system

We examine a binary model where the secondary is a main sequence star of mass $M_1 \approx 0.3 - 0.5M_\odot$. If we take the primary post-RGB star to be of mass $M_2 \approx 0.45M_\odot$ and a post-AGB to be of mass $M_1 \approx 0.55M_\odot$ (e.g., Bloecker 1993), then these two cases span a mass ratio of $q = M_2/M_1 \approx 0.6 - 1$. Using the expression for the Roche lobe radius $r_L$ from Eggleton (1983), we find for the primary star $r_{L1}/a = 0.42$ and 0.38 for $q = M_2/M_1 = 0.6$ and 1, respectively, where $a$ is the orbital separation. For the secondary star we find $r_{L2}/a = 0.34$ and 0.38 for $q = M_2/M_1 = 0.6$ and 1, respectively. For an orbital period of $P = 4.2$ h the orbital separation (for a circular orbit) is $a = 1.27(M/0.9M_\odot)^{1/3}R_\odot$, and the Roche lobe of the primary star is

$$r_{L1} = 0.51 \left( \frac{M}{0.9M_\odot} \right)^{1/3} \left( \frac{r_{L1}/a}{0.4} \right) R_\odot,$$

(1)

where $M = M_1 + M_2$ is the total binary mass. From the primary luminosity, $L_1 = 845(D/1.4$ kpc)$^3L_\odot$, and for the effective temperature assumed here, the primary radius is

$$R_1 = 0.48 \left( \frac{D}{1.4 \text{ kpc}} \right) \left( \frac{T_1}{4.5 \times 10^4 \text{ K}} \right)^{-2} R_\odot.$$  

(2)

For a distance of $D = 1.8$ kpc the primary radius with that effective temperature is $R_1 = 0.62R_\odot$, but taking a temperature $T_1 = 50,000$ will make the primary just filling in its Roche lobe. In our model the primary is close to filling its Roche lobe (assuming synchronization). For the secondary the Roche lobe radius is in the range $r_{L2} \approx 0.42 - 0.5R_\odot$. Thus, the secondary also touches its Roche lobe.

3.2 Evolution

We consider two possible evolutionary scenarios. We prefer the post-RGB one, but cannot rule out the post-AGB one. We first describe the relevant evolution tracks on the Hertzsprung-Russell diagram, and then turn to discuss the two possible scenarios.

3.2.1 Evolutionary tracks

In the top panel of Fig. 1 we present some relevant evolutionary tracks on the Hertzsprung-Russell diagram, together with the approximate location of the central star of Henize 2–428 at two distances, $D = 1.4$ kpc (square) and 1.8 kpc (asterisk), and the position reported by Santander-Garcia et al. (2015), filled circle, and the central star in our proposed scenario when the distance is $D = 1.4$ kpc (filled square) and when $D = 1.8$ kpc (asterisk).
tion of zero-age main sequence (ZAMS) stars with masses $M_{\text{ZAMS}} = 1.5$ and $5.0 M_\odot$, respectively, of Solar metallicity. The evolution is followed through all the relevant stages, including the hydrogen and helium core burning phases, the thermally-pulsing AGB phase, and the post-AGB evolution to the white dwarf stage. The $M_1 = 0.540 M_\odot$ sequence was also taken from Renedo et al. (2010), and corresponds to a progenitor of mass $M_{\text{ZAMS}} = 0.85 M_\odot$ with $Z = 0.001$. In addition, the post-RGB evolution of a $0.432 M_\odot$ helium-core low-mass white dwarf is included. This sequence is the result of the non-conservative binary evolution of a star of mass $M_{\text{ZAMS}} = 1.0 M_\odot$ that abandons the RGB before the onset of core helium burning (Althaus et al. 2013). Finally, the evolutionary track of a $M_1 = 0.84 M_\odot$ post-AGB remnant of a $M_{\text{ZAMS}} = 3.0 M_\odot$ progenitor with metallicity $Z = 0.001$ that experiences a late thermal pulse (LTP) when its effective temperature was $T_{\text{eff}} = 10,000 K$ is shown as well. As a result of the LTP, the post-AGB remnant experiences a fast evolution to the blue. After reaching a maximum effective temperature, this remnant evolves back to the domain of giant stars.

Note that the luminosity inferred for Henize 2–428, for the effective temperatures used by Santander-Garcia et al. (2015) and by us, is substantially smaller than that predicted by post-AGB evolutionary models for masses of $M_{\text{ZAMS}} > 0.55 M_\odot$. The claimed masses for the two central stars of Henize 2–428 do not fit the other claimed properties of the stars in the model proposed by Santander-Garcia et al. (2013). However, the $M_1 = 0.504$ post-AGB star presented here (upper panel) experiences an LTP at $T_{\text{eff}} = 48,000 K$, which brings the remnant back rapidly to the red giant domain and finally to the white dwarf stage. Such an evolutionary track covers the general region of Henize 2–428 on the Hertzsprung-Russell diagram.

Finally, the bottom panel of Fig. 1 displays the evolution of a star with $M_{\text{ZAMS}} = 2.5 M_\odot$, and $Z = 0.01$. The evolution of this star was truncated on the lower AGB, when its luminosity is $L = 1,400 L_\odot$, the observed luminosity of the binary system for the distance we adopt. At this point mass was removed to mimic a common-envelope episode. The final mass of the remnant after this intense episode of mass loss is $0.50 M_\odot$. The evolution in the Hertzsprung-Russell diagram of this sequence shows several blue loops, which are due to successive ignitions of the hydrogen shell.

As can be seen, this track is also able to reproduce the observed position of Henize 2–428, for our adopted distance.

In conclusion, post-RGB helium-core remnants with stellar masses of $M_1 \approx 0.45 M_\odot$ and low-mass cores of AGB stars that truncate the lower AGB with masses of $M_1 \approx 0.5 – 0.55 M_\odot$ can account for the central star of Henize 2–428.

3.2.2 Post-RGB evolution

Guerrero et al. (2000) studied 15 bipolar PNe, and only in Henize 2–428 they detect no H$_2$ emission, and it was the only PN in their sample in which a bright central star was found. It seems there is something strange in the evolution of this PN, which here is attributed to the system being a post-RGB star. Rodríguez et al. (2001) found the low abundances of most elements they study (relative to hydrogen) of Henize 2–428 to be similar to those found for PNe belonging to the Galactic halo. They suggested that this points to a low-mass progenitor. It is quite possible that the central star of Henize 2–428 is a post-RGB star orbited by a low-mass main sequence star. The post-RGB scenario is compatible with the low nebular mass, as the initial stellar mass in this scenario is $M_{\text{ZAMS}} \approx 1 M_\odot$, and the post-RGB mass is $M_1 \approx 0.45 M_\odot$.

3.2.3 Post-AGB evolution

In this proposed alternative scenario the evolution of the primary star is truncated on the lower AGB when its luminosity is $\approx 1000 – 1500 L_\odot$ and its radius is $\approx 150 R_\odot$, assuming in this case a distance of $D = 1.8$ kpc. The core mass is $\approx 0.5 – 0.55 M_\odot$ (e.g., Bloecker 1993; Fig. 1 here). The companion will spiral-in due to tidal forces when the primary radius is about quarter of the orbital separation (Soker 1996). The initial orbital separation in this scenario is therefore $a_0 \approx 3$ AU.

To avoid engulfment already on the RGB phase of the primary star, the primary size on the RGB must be $< 100 R_\odot$, which limits the initial mass of the primary star to be $2.3 \lesssim M_{\text{ZAMS}} \lesssim 6 M_\odot$ (Iben & Tutukov 1985). Therefore, in this scenario the AGB star is more massive, and a more massive nebula is expected.

4 SUMMARY

We addressed the recent claim made by Santander-Garcia et al. (2015) that the central binary system of the planetary nebula Henize 2–428 is a progenitor of a SN Ia in the frame of the double-degenerate scenario. This claim has attracted quite an attention, as if true it would be the first short super-Chandrasekhar mass binary WD system discovered ever. More interestingly, it would be definitely located in the center of a planetary nebula. However, we found that this extraordinary claim is not yet fully supported by the observations presented in that paper.

In sections 2.1 and 2.2 we argued that the claim for an equal-masses binary system and the required mass, luminosity, and radius of the two stars do not comply with evolutionary tracks of post-AGB stars (see also Fig. 1). In section 2.3 we find their explanation to the double-troughs profile of the He II 5412 Å absorption spectral line as arising from Doppler shifts of two absorption lines, one from each star, to be unsatisfactory.

Also, in section 2.3 we suggested that the variability of the He II 5412 Å spectral line can be accounted for by a possibly time-varying, broad absorption line from the central star on top of which there is a time-varying narrow emission line from the compact nebula or even from much closer to the star (Dobrinic et al. 2008). We find the age of the Henize 2–428 equatorial ring to be $4300 (D/1.8$ kpc) yr. Although the ring is old, there is a compact dense nebula near the central star (Rodríguez et al. 2001). It is quite possible that the He II 5412 Å narrow emission spectral line sitting on top of the broad absorption line originates in the compact nebula, or from an outflow that feeds the compact nebula much closer to the star.

We then argued that other explanations, less extraordinary but that fit better with observations and stellar evolu-
solution, exist. Our scenarios still hold the existence of a binary system, as the two (almost) symmetric broad minima in the light curve are attributed to tidal distortion caused by a companion of similar mass. In particular we mentioned a binary system composed of either a post-RGB or a post-AGB star with a low-mass companion (section 3.1). In the first case, discussed in sections $3.2.1$ and $3.2.2$, a low-mass main sequence star truncates the evolution of a star of initial mass $M_{ZAMS} \approx 1M_\odot$ on the upper RGB. In the second scenario discussed in sections $3.2.1$ and $3.2.3$, a main sequence star truncates the evolution of a star of initial mass $M_{ZAMS} \approx 2.5 - 3M_\odot$ on the lower AGB.

We conclude this short study by stating that if our interpretation is correct, the central binary system of the planetary nebula Henize 2–428 is unlikely to explode as a SN Ia, and hence cannot be claimed yet to support the double-degenerate scenario for type Ia supernovae.

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