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

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HIGHLIGHTS

- We discuss the binary system in the planetary nebula Henize 2–428.
- The explanation of two equal-mass stars leading to a SN Ia is premature.
- The nature of the central binary system of Henize 2–428 is still open.

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ABSTRACT

We critically discuss the recent observations of the binary system at the center of the bipolar planetary nebula Henize 2–428. We find that the proposed explanation of two equal-mass degenerate objects with a total mass larger than the Chandrasekhar limiting mass that supposedly will merge in less than a Hubble time, possibly leading to a SN Ia, is controversial. This hypothesis relies on the assumption that the variability of the He II 5412 Å spectral line is due to two absorption components. Instead, we propose that it can be accounted for by a broad absorption line from the central system on top of which there is a narrow emission line from the nebula. This prompted us to study if the binary system can be made of a degenerate star and a low-mass main sequence companion, or of two degenerate objects of smaller mass. We find that although both scenarios can account for the existence of two symmetric broad minima in the light curve, the second one agrees better with observations. We thus argue that the claim that Henize 2–428 provides observational evidence supporting the double-degenerate scenario for SN Ia is premature.

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 that produce 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 and Soker (2015) for a recent discussion of some of the channels, and Wang and 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 and Riess, 2003; Kashi and Soker, 2011; Soker et al., 2013), (b) the double-degenerate (DD) scenario (e.g., Webbink, 1984; Iben and Tutukov, 1984), (c) the double-detonation (DDet) mechanism (e.g., Woosley and Weaver, 1994; Livne and Arnett, 1995; Shen et al., 2013. (d) The single-degenerate (SD) scenario (e.g., Whelan and Iben, 1973; Nomoto, 1982; Han and Podsiadlowski, 2004), e) The recently proposed singly-evolved star (SES) scenario (Chiosi et al., 2015), and f) The WD-WD collision (WWC) scenario (e.g., Raskin et al., 2009; Thompson, 2011; Kushnir et al., 2013; Aznar-Siguán et al., 2013).

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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. Furthermore, in some cases SN Ia have been even claimed to take place inside planetary nebulae (e.g., Dickel and Jones, 1985; Tsebrenko and Soker, 2013; 2015), a process termed SNIP.

In a recent paper Santander-García et al. (2015) analyzed the central binary system of the planetary nebula Henize 2–428 (Rodríguez et al., 2001; Santander-García et al., 2011). Santander-García et al. (2015) found that the light curve of this PN shows two nearly identical broad minima, indicating significant tidal distortion of the components of binary system, 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 identical, they assumed that they are caused by a binary system composed of two equal-mass stars of the same type, and found the temperature, radius, and luminosity, of the two stars to be almost identical. They further argued 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 $1.76\,M_\odot$, Santander-García et al. (2015) further argued that these two stars will merge to form a SN Ia in the frame of the DD scenario.

Here we critically discuss the explanation of Santander-García et al. (2015). As we explain in Section 2 we find the interpretation of the observations of Santander-García et al. (2015) to be plausible, albeit other possibilities are conceivable. In Section 3 we relax the assumptions of these authors and we propose alternative models of the binary system. The first of these models consists of binary system in which only one of the components is a degenerate star, while the secondary star is normal non-evolved star. The second of the models involves two non-identical degenerate stars, but with a combined mass smaller than the Chandrasekhar limiting mass. A short summary is given in Section 4.

2. Preliminary considerations

2.1. A binary system made of two identical stars

Santander-García et al. (2015) argue for a binary system composed of two stars having the same mass, $0.88 \pm 0.13\,M_\odot$, the same luminosity, $\approx 420\,L_\odot$ at a distance of 1.4 kpc, and the same radius, $0.68 \pm 0.04\,R_\odot$. 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 $0.88\,M_\odot$ burns hydrogen at a rate of $\sim 2 \times 10^{-7}\,M_\odot\ \mathrm{yr}^{-1}$ (e.g., Paczyński, 1970). For a difference in mass between the two cores $< 0.02\,M_\odot$ the difference of evolutionary times between the post-AGB stars should be $\lesssim 10^5$ 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.

It could be argued that there are other binary systems with almost identical components, known as twin binaries (Lucy and Ricco, 1979). Specifically, Pinsonneault and Stanek (2006) studied 21 detached eclipsing binaries in the Small Magellanic Cloud and found that 50% of detached binaries have companions with very similar masses. However, Lucy (2006) and Cantrell and Dougan (2014) concluded that there is a strong observational bias that affects spectroscopically selected binary stars, and that the apparent overabundance of twin binaries does not reflect their true population. In summary, the case for a twin binary is possible, but unlikely, hence motivates us for a careful reexamination of such a claim.

2.2. Stellar properties

As mentioned, in the model proposed by Santander-García et al. (2015) each star is a post-AGB star with a mass of $0.88\,M_\odot$. When a post-AGB of that mass fades to a luminosity of $\approx 10^3\,L_\odot$ its radius is already $\simeq 0.02\,R_\odot$ (e.g., Bloecker and Schoenberner, 1991). This radius is about 30 times smaller than the radius suggested by Santander-García et al. (2015). This poses a serious problem to their model.

In the first of our models we investigate a case where the luminosity of the system is due to just one star, and the luminosity of the companion is negligible — see below for more details. At a distance of $D = 1.4$ kpc as deduced by Santander-García et al. (2015) the luminosity is $\approx 850\,L_\odot$. This can be a star whose evolution was truncated on the upper red giant branch (RGB), when its core mass was only $M_1 \approx 0.45\,M_\odot$, or on the lower AGB when its core mass was $\approx 0.5\,M_\odot$. On the other hand, if the distance is larger, say $D = 1.8$ kpc, the luminosity is $\approx 1.4 \times 10^3\,L_\odot$. This can be a star whose evolution was truncated on the lower AGB, when its core mass was only $M_1 \approx 0.52 - 0.55\,M_\odot$. In our proposed model the companion that terminated the RGB or the AGB evolution of the primary component is a main sequence star of $\sim 0.3 - 0.5\,M_\odot$. In the second of our models we assume that indeed both stars are post-AGB stars but we allow the stars to have different physical parameters, namely different masses, effective temperatures and luminosities.

A note is in place here on the distance to Henize 2-428. Santander-García et al. (2015) provided a rough estimate of the distance of 1.4 ± 0.4 kpc based on the dereddened apparent magnitudes of Henize 2–428. Maciel (1984) obtained a distance of 1.7 kpc, Cahn and Kaler (1971) derived a distance of 2.7 kpc, while the most recent determination of Frew et al. (2015), using the Hα surface brightness–radius relation is also 2.7 kpc. Based on these values we will scale our expressions with two distances, $D = 1.4$ kpc and $D = 1.8$ kpc, as the value adopted by Santander-García et al. (2015) was obtained from their fit to the properties of the binary system, which is questioned here.

2.3. Light curves and spectrum

The arguments of Santander-García et al. (2015) for their claim of a binary system of equal-mass stars at the same evolutionary stage are the nearly identical minima in the light curve, and the line profile of the He II 5412 Å spectral feature — see their Figs. 2 and 3. The nearly identical minima of the light curve have been suggested to be indicative that both members of the binary system have very similar masses. In additional, Santander-García et al. (2015) found that the He II 5412 Å spectral line of Henize 2–428 is variable. They attributed the variability of this line to Doppler shifts of two equal-mass stars, and then used two Gaussian absorption profiles to model the variation. Consequently, in their joint analysis of the light curve and the spectrum they *forced* the mass ratio $q = M_2/M_1$ of the binary system to be 1. Furthermore, Santander-García et al. (2015) *did not model the spectra* of both components of the binary system, since they were not able to measure surface gravities for each one of the individual binary members. Finally, they *assumed* that both stars are at the same evolutionary stage. All of these assumptions are critical in their analysis.

In particular, it must be stressed that even if the mass ratio is close to 1, the nature of the stars can be very different, and that the lack of determinations of surface gravities leaves room for alternative explanations. In particular, a close look at Figs. 2 and 3 of Santander-García et al. (2015) suggests that the spectrum of Henize 2–428 can be explained by assuming that there is an emission line on top of the absorption profile. We therefore examine a possible alternative interpretation where 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 which originates even much closer to the star from the wind itself. In this alternative explanation both emission and absorption lines change with orbital phase. This is not unusual. Many central stars of planetary nebulae show He II absorption lines (e.g., Weidmann and Gamen, 2011). The emission line is seen in some nebulae, e.g.,