Binary Paths to Type Ia Supernovae Explosions
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A Search for Type Ia Supernova Progenitors: the Central Stars of the Planetary Nebulae NGC 2392 and NGC 6026

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Abstract. We use photoionization modeling to assess the binary nature of the central stars of NGC 2392 and NGC 6026. If they are close binaries, they are potential Type Ia supernovae (SNe Ia) progenitors if the total mass exceeds the Chandrasekhar limit. We show that the nucleus of NGC 2392 likely has a hot, massive ($\simeq 1\,M_{\odot}$) white dwarf companion, and a total mass of $\sim 1.6\,M_{\odot}$, making it an especially interesting system. The binary mass in NGC 6026 is less, $\sim 1.1\,M_{\odot}$. Even though its orbital period is short, it is not considered to be an SNe Ia progenitor.

Keywords. planetary nebulae: individual (NGC 2392 & NGC 6026) — supernovae: general

1. Introduction

A proposed pathway for the generation of Type Ia supernovae (SNe Ia) is via the merger of two white dwarfs (WDs), the so-called double-degenerate channel (Webbink 1984). Until recently, the sample of known double degenerates was limited to older WDs. However, recent work has shown that a few planetary nebula central stars (CSPN) are likely (pre-) double-degenerate binaries. In this work, we use 1-D (CLOUDY; Ferland *et al.* 1998) and 3-D (MOCASSIN; Ercolano *et al.* 2003) photoionization codes to infer the nature of the central binary stars in two planetary nebulae (PNe). Constraints on their component masses will show if the total mass exceeds the Chandrasekhar limit. If these systems are short-period binaries, they are potential SNe Ia progenitors.

2. NGC 2392

The bright Eskimo nebula (NGC 2392) has a conspicuous hydrogen-rich CSPN with $T_{\rm eff} = 43{,}000$ K (Méndez et al. 2011). However, the surrounding PN has emission lines of high excitation, such as He II $\lambda 4686$ and [Ne V] $\lambda 3426$, which cannot be produced by the visible star. An additional hot ionizing source must be present. To deduce the properties of the companion, we model the PN using MOCASSIN. For the model inputs, we used the line intensities from Pottasch *et al.* (2008), and adopt a distance of 1.8 kpc. Following O'Dell *et al.* (1990), the model has a heterogeneous density distribution, with $n_{\rm e} = 3000$ and 1300 cm^{-3} for the inner prolate spheroid and outer spherical zone, respectively (see Figure 1 in Danehkar *et al.* 2011). Our model outputs agree well with the observations (see Table 1), and we find that a hot, massive WD with $T_{\rm eff} = 250$ kK is a plausible source of the extra UV photons. The WD mass from evolutionary tracks is close to 1 $M_{\odot}$, so the total mass may exceed the Chandrasekhar limit. If the system is a close binary (Méndez *et al.* 2011), the stars may merge within a Hubble time, making it a potential SN Ia progenitor. It is interesting to note that Guerrero *et al.* (2011) have found the CSPN

Table 1. Best-fit parameters (left) and observations versus model outputs (right).

Parameter	NGC 2392	NGC 6026
T_1^* (K)	43 000	37 500
L_1^* ($L_\odot$)	7 600	1 500
M_1^* ($M_\odot$)	0.63	0.54
T_2^* (K)	250 000	146 000
L_2^* ($L_\odot$)	650	750
M_2^* ($M_\odot$)	1.0:	0.60:
R_{in} (pc)	0.07	...
$n_{e\,(in)}$ (cm^{-3})	3000	...
R_{out} (pc)	0.22	0.24
$n_{e\,(out)}$ (cm^{-3})	1300	330
T_e (K)	14 500	15 000
ε	0.07	0.3
He/H	0.08	0.10
N/H	1.9(−4)	6.3(−5)
O/H	2.9(−4)	1.6(−4)
Ne/H	8.5(−5)	3.2(−5)
S/H	7.0(−6)	5.8(−6)
Ar/H	2.2(−6)	7.9(−7)

Object		NGC 2392		NGC 6026	
Ion	λ(Å)	Obs.	Mod.	Obs.	Mod.
[Ne V]	3426	4.0	2.3	...	19
[O II]	3727	110	107	...	8
[Ne III]	3869	105	130	34:	61
Hγ	4340	47	47	56	48
He II	4686	37	35	78	89
Hβ	4861	100	100	100	100
[O III]	5007	1150	1143	709	693
[N II]	5755	1.6	2.6	<1.0	0.4
He I	5876	7.4	7.5	<14	2.7
Hα	6563	285	282	286	282
[N II]	6584	92	129	12	12
[S II]	6717	6.7	3.2	2.5:	6.3
[S II]	6731	8.6	4.6	2.2:	5.7
[Ar III]	7135	14	12	9::	6.0
[S III]	9532	91	94	...	60
L(Hβ)[erg/s]	1E33	25	20	4.3	5.7

to be a hard X-ray source. which may point to mass transfer between the components. Further observations of this unusual PN and its central star are urged.

3. NGC 6026

Similarly to the Eskimo, spectra show that the excitation class of this elliptical PN is too high to be the result of photoionization by the observed CSPN. This was recently found to be a short-period binary with $P = 0.528$ days (Hillwig et al. 2010). Based on light-curve modeling, the system consists of a relatively cool O7 star ($T_{\rm eff} = 38$ kK) and an unseen companion, which is a hot WD with $T_{\rm eff} = 146$ kK. The luminosity and mass of the components, the PN distance, and the nebular abundances were independently determined here by interpolating from a grid of CLOUDY models. The distance is 2.0 ± 0.5 kpc, and the luminosities and masses of the components are given in Table 1. Despite the short orbital period, the total mass is too low for the system to produce an SN Ia. Lastly, we find that the PN progenitor had sub-solar metallicity, with [O/H] $\simeq -0.5$ dex.

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