PHOTOIONIZATION MODELS OF THE ESKIMO NEBULA: EVIDENCE FOR A BINARY CENTRAL STAR?

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Introduction

The bright, double-envelope planetary nebula NGC 2392, nicknamed the Eskimo nebula, has a conspicuous 11th-magnitude hydrogen-rich central star with well determined parameters. The effective temperature of the central star, derived from conventional spectral-line fitting, is 43,000 K (Méndez et al. 2011). However, the surrounding planetary nebula has emission lines of high and very-high excitation, such as He II 4686 and [Ne V] 3426 (Pottasch & Bernard-Salas 2010) which cannot be produced by the observed central star. In particular, the presence of [Ne V] 3426 implies $T_{eff} > 100{,}000$ K for the embedded ionizing source. It seems that an additional hot companion star is required to supply the hard-UV radiation field, likely to be another white dwarf. If this is the case, the central star of the Eskimo will be a valuable addition to the small sample of PNe with double-degenerate nuclei.

In this work, we aim to estimate the luminosity, temperature and mass of the optically invisible secondary star in NGC 2392 through photoionization modeling. We use the 3-D photoionization code MOCASSIN (Ercolano et al. 2003) to model the PN emission. We also investigate an alternative hypothesis, i.e. that the high-excitation lines are due to shocks produced by a fast bipolar outflow from the central star. We use the 1-D shock ionization code Mappings-III (Binette et al. 1985; Sutherland & Dopita 1993) to test the feasibility of this hypothesis, and to estimate the shock parameters that would be required to produce the observed higher ionization species.

Observational Data

We adopt the observed nebular line intensities from Pottasch et al. (2008). The PN physical parameters and stellar characteristics were obtained as follows:

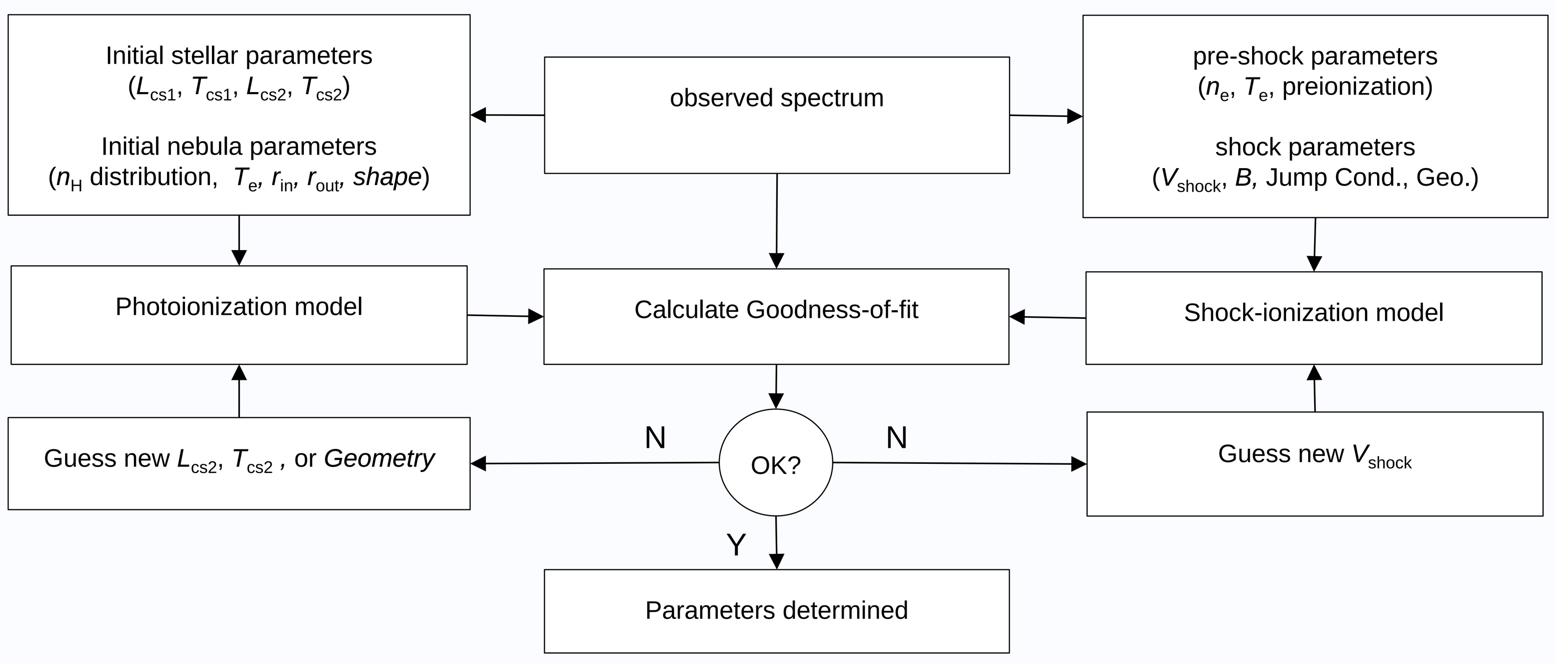
1. [S III] 6731/6716, [O II] 3626/3729, and [S III] 33.5μm/18.7μm for the electron density (n_e).
2. [N II] 6548+6583/5755, [S III] 1883+1892/1206, [Ar III] 7136+7751/5192, and [Ne III] 3869+3969/3342 for the electron temperature (T_e).
3. The ionic abundances were calculated using ionization correction factors from Pottasch & Bernard-Salas (2010) and corrected using our photoionization grid.
4. The effective temperature (T_{cs1} = 43kK) of the visible star is derived from the observed stellar H and He absorption lines (Méndez et al. 1988).
5. The PN distance is adopted from Pottasch et al. (2011).
6. A volume filling factor of 0.07 is adopted (see Boffi & Stanghellini 1994).

Table 1. NGC 2392 Input parameters.

Parameters	Value
L_{cs1} (L_{sun})	7,600
T_{cs1} (K)	43,000
M_1 (M_{sun})	0.63
L_{cs2} (L_{sun})	650
T_{cs2} (K)	250,000
M_2 (M_{sun})	1.0:
$n_{inner\ shell}$ (H cm^{-3})	3000
$R_{inner,\ inside\ shell}$ (pc)	0.07
$R_{outer,\ inside\ shell}$ (pc)	0.09
$n_{outer\ shell}$ (H cm^{-3})	1300
$R_{inner,\ Outside\ shell}$ (pc)	0.09
$R_{outer,\ Outside\ shell}$ (pc)	0.22
T_e (K)	14,500
Distance (pc)	1800
Filling Factor	0.07
Geometry	elliptical
log $(He/H)_{+12}$	10.90
log $(C/H)_{+12}$	8.52
log $(N/H)_{+12}$	8.27
log $(O/H)_{+12}$	8.46
log $(Ne/H)_{+12}$	7.93
log $(S/H)_{+12}$	6.85
log $(Ar/H)_{+12}$	6.34

Modeling

- The photoionization modeling shows that a spherical geometry cannot account for the observed strong lines such as [N II] 6584 and [O II] 3727. It is necessary to use an inhomogeneous density distribution, i.e. a double-envelope with a dense, inner prolate spheroid and a lower density outer zone (Figure 1).
- A blackbody with T_{eff} = 43kK and L/L_{sun} = 7600 cannot produce the observed values of He II 4686 and [Ne V] 3426, so a putative hotter companion is necessary. We derived T_{eff}>200kK and L/L_{sun}< 1000 using a grid of photoionization models.
- Shocks can also account for the low-ionization structures (LIS), seen in the [S II] 6731 image (Figure 2). These are hard to explain using a pure photoionization model.



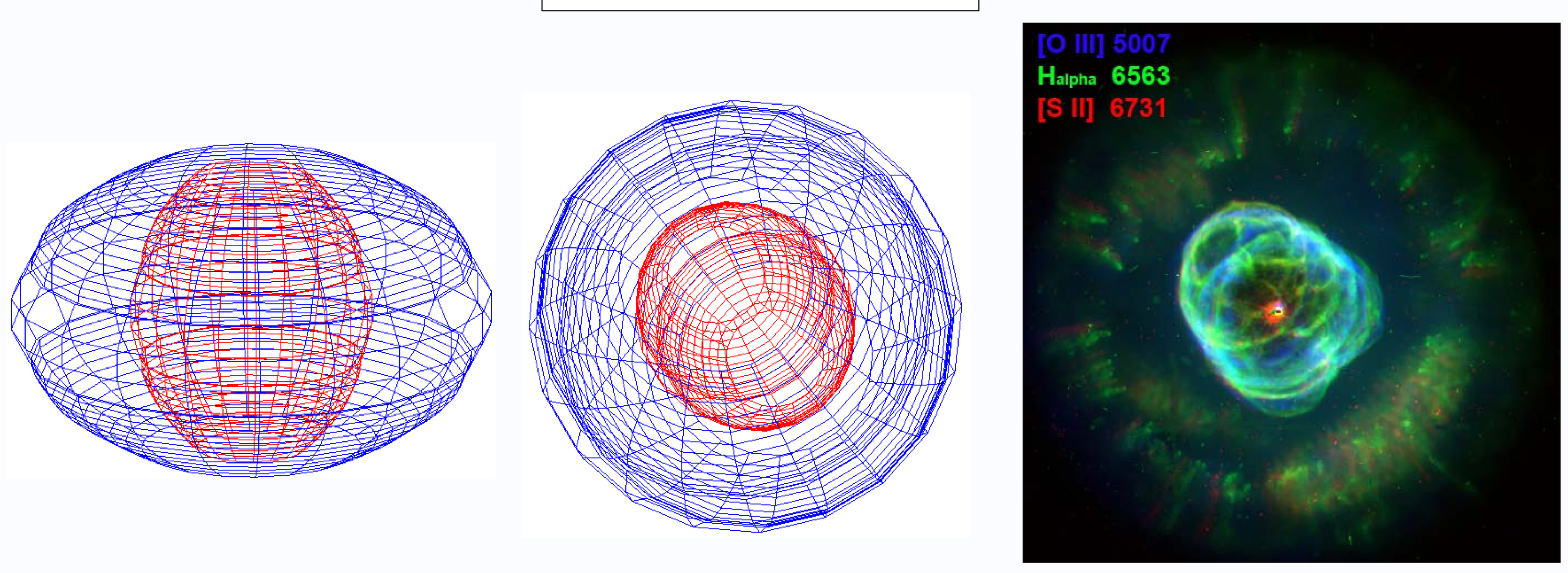


Figure 1. The assumed double-envelope morphology containing a dense inner prolate shell and a lower density outer zone. The nebular orientation is near face-on. This morphology was used as a model input for MOCASSIN.

Results

We calculated a goodness-of-fit for variation of the luminosity and effective temperature of the putative binary companion. We compare the photo-ionization results with the observed optical spectrum.

The density distribution was constructed based on narrow-band Hα, [O III] and [N II] images and kinematic data following O'Dell et al. (1990). A simple assumption of spherical geometry leads to disagreement with the observed ionization structure and nebular line intensities.

The plane-parallel shock models were adopted to estimate the shock velocity required to reproduce the observed ionization structure. The ionic abundances are the same as the photoionization model.

Table 2. Model results.

Parameter	Model 1	Model 2	Model 3
L_{cs1} (L_{sun})	7,600	-	7,600
T_{cs1} (kK)	43	-	43
L_{cs2} (L_{sun})	-	650	650
T_{cs2} (kK)	-	250	250
Shocks	No	No	No

Line (Å)	Ion	Obs.[1]	Model 1	Model 2	Model 3
3426	[Ne V]	4.0	0.04	0	2.3
3727	[O II]	110	100	861	107
3869	[Ne III]	105	100	159	130
4101	Hδ	25	26	26	26
4340	Hγ	47	47	47	47
4686	He II	37	22.5	35	35
4861	Hβ	100	100	100	100
5007	[O III]	1150	916	19	1143
5755	[N II]	1.6	2.2	36	2.6
5876	He I	7.4	9	14	7.5
6312	[S III]	3.2	2.4	3.7	2.9
6563	Hα	285	284	284	282
6584	[N II]	92	128	2035	129
6717	[S II]	6.7	3.3	176	3.2
6731	[S II]	8.6	4.7	188	4.6
7135	[Ar III]	14	12.6	36	12
9532	[S III]	91	92	139	94
L(Hb) erg/s	E33	25	21	5	20

[1] Pottasch et al. (2008).

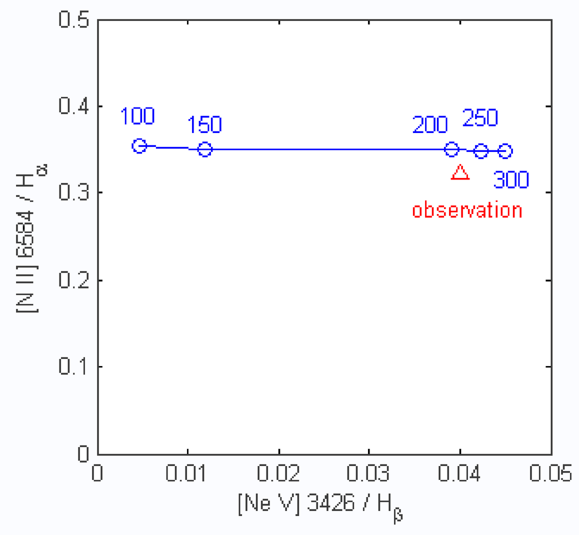
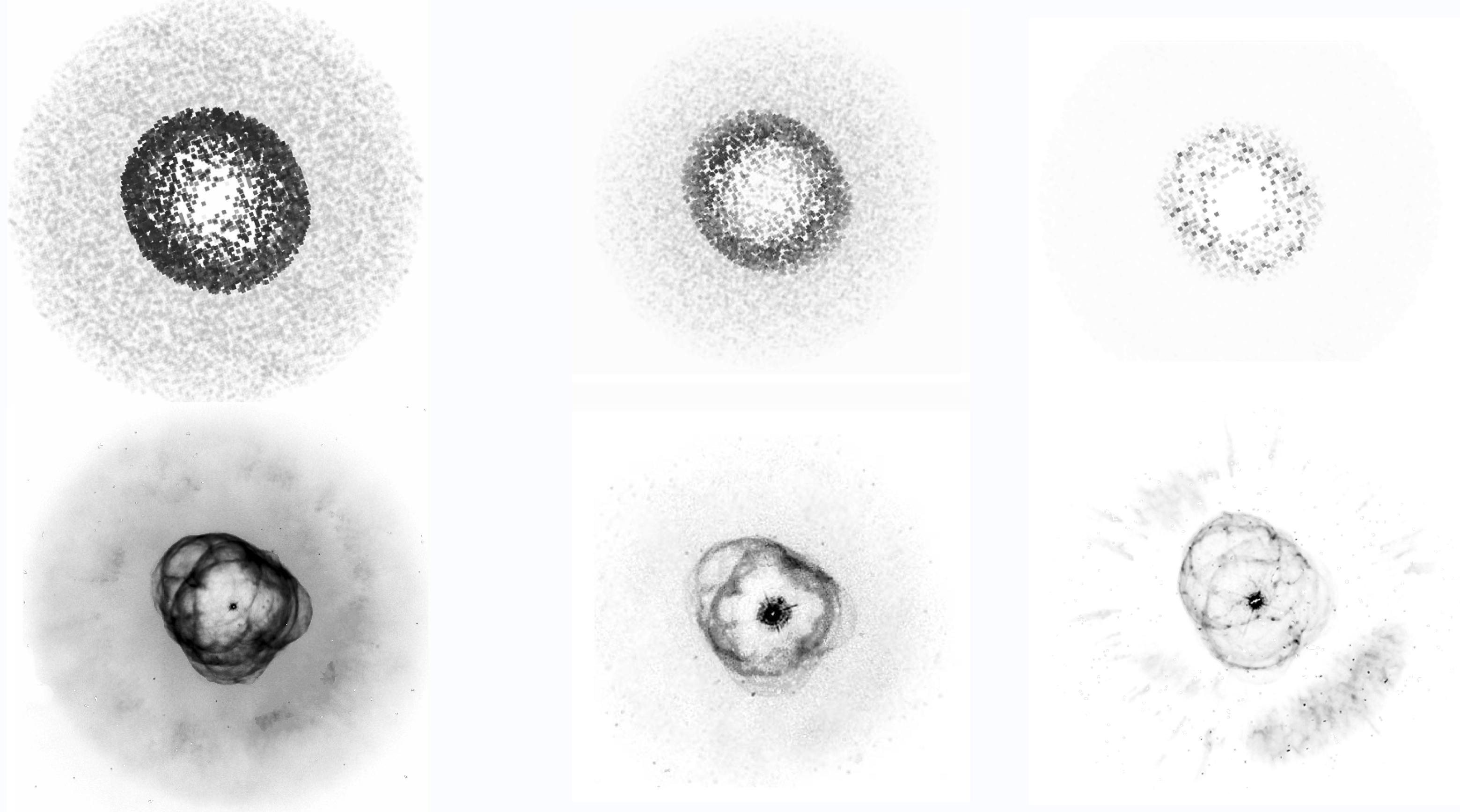


Fig. 2. shock-ionization results in terms of line ratios, as compared to the observed lines for V_{shock} of 100, 150, 200, 250 and 300 km s^{-1} and $F_{photo+shock} = A_{A/S} \times F_{shock} + (1 - A_{A/S}) \times F_{photo}$, $A_{A/S}$=0.1.

Table 3. NGC 2392 shock parameters.

Parameter	Model 4
Code	Mappings III
$n_{preshock}$ (cm^{-3})	400
$Te_{preshock}$ (K)	4000
V_{shock} (kms^{-1})	100-300
Geometry	Plane-Parallel
Stop T	Te < 1,000K



[O III] 5007 He II 4686 [S II] 6731

Figure 3. Computed surface brightness of NGC 2392 compared with the *HST* image.

Conclusions

Our first attempt to determine the stellar characteristics of the putative secondary shows that a hot WD companion with T_{eff} = 250 kK and L/L_{sun} = 650 is a plausible source for the additional ionizing photons.

The core masses derived from standard evolutionary tracks (Fig. 4) will help us to understand the evolution of this interesting system. The total mass is estimated to be 1.4 $M_{\odot}$, which is close to the Chandrasekhar limit. If the stars form a close binary, they may merge within a Hubble time and the system is a potential SN Ia progenitor!

While various shock models can roughly explain the visible [Ne V] emission and the LIS seen in the outer shell, they fail to reproduce the ionization structure of the other lines.

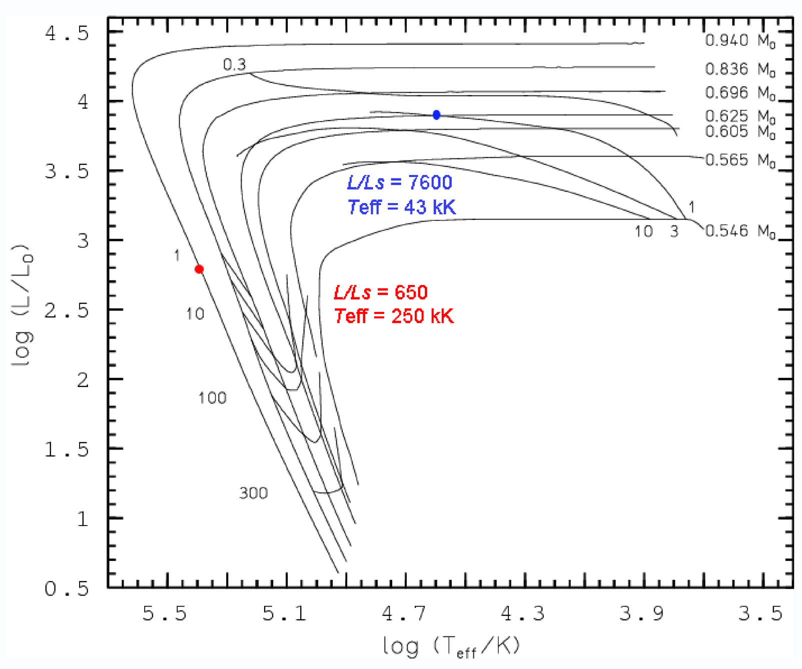


Figure 4. The two components of the central binary plotted on the theoretical Hertzsprung-Russell diagram (Perinotto et al. 2004).

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