*From Interacting Binaries to Exoplanets: Essential Modeling Tools*
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# Photoionization Models of the Eskimo Nebula: Evidence for a Binary Central Star?

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**Abstract.** The ionizing star of the planetary nebula NGC 2392 is too cool to explain the high excitation of the nebular shell, and an additional ionizing source is necessary. We use photoionization modeling to estimate the temperature and luminosity of the putative companion. Our results show it is likely to be a very hot ($T_{\rm eff} \simeq 250$ kK), dense white dwarf. If the stars form a close binary, they may merge within a Hubble time, possibly producing a Type Ia supernova.

**Keywords.** Planetary nebulae: individual (NGC 2392); photoionization codes; shock models

## 1. Introduction

NGC 2392 is a bright, double-envelope planetary nebula (PN), nicknamed the Eskimo nebula, with a bright hydrogen-rich central star (CSPN). The effective temperature, derived from spectral-line fitting, is 43 kK (Méndez *et al.* 2011). However, the surrounding PN exhibits high-excitation emission lines, such as He II $\lambda$4686 and [Ne V] $\lambda$3426, which cannot be produced by the visible star. In particular, the presence of [Ne V] implies $T_{\rm eff} > 100$ kK for the ionizing source. It seems that a hot companion is needed to supply the hard-UV photons, likely to be a white dwarf. If this is the case, the Eskimo will be a valuable addition to the small sample of PNe with (pre-)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 code MOCASSIN (Ercolano *et al.* 2003) to model the PN emission lines. 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 CSPN. We use the 1-D shock ionization code Mappings-III (Sutherland & Dopita 1993) to test the feasibility of this hypothesis.

## 2. Modeling

We initially adopted the observed nebular line intensities and abundances (except log S/H = −5.16) from Pottasch *et al.* (2008), and used plasma diagnostics to derive the electron temperature and density in the usual way. We adopted a distance of 1.8 kpc following Pottasch *et al.* (2011). As expected, the photoionization modeling showed it was necessary to use a model with a heterogeneous density distribution. This was constructed from narrow-band images and kinematic data following O'Dell *et al.* (1990), and we adopted densities of 3000 and 1300 cm$^{-3}$ for the inner prolate spheroid and outer zone, respectively. We used NLTE model atmosphere fluxes from the grid of Rauch (2003). Our first attempt to determine the characteristics of the putative companion shows that a very hot, high-gravity white dwarf with $T_{\rm eff} = 250$ kK and $L/L_\odot = 650$ is a plausible source of the additional ionizing photons. We compare our results with the observed spectrum in Table 1, and compare the model output to the [O III] image in Figure 1.

**Table 1.** Photoionization model output versus observations.

| Ion | $\lambda$(Å) | Obs. | Mod. | Ion | $\lambda$(Å) | Obs. | Mod. |
|---|---|---|---|---|---|---|---|
| [Ne V] | 3426 | 4.0 | 2.3 | [N II] | 5755 | 1.6 | 2.6 |
| [O II] | 3727 | 110 | 107 | He I | 5876 | 7.4 | 7.5 |
| [Ne III] | 3869 | 105 | 130 | H$\alpha$ | 6563 | 285 | 282 |
| H$\gamma$ | 4340 | 47 | 47 | [N II] | 6584 | 92 | 129 |
| [O III] | 4363 | 19 | 13 | [S II] | 6717 | 6.7 | 3.2 |
| He II | 4686 | 37 | 35 | [S II] | 6731 | 8.6 | 4.6 |
| H$\beta$ | 4861 | 100 | 100 | [Ar III] | 7135 | 14 | 12 |
| [O III] | 5007 | 1150 | 1143 | [S III] | 9532 | 91 | 94 |

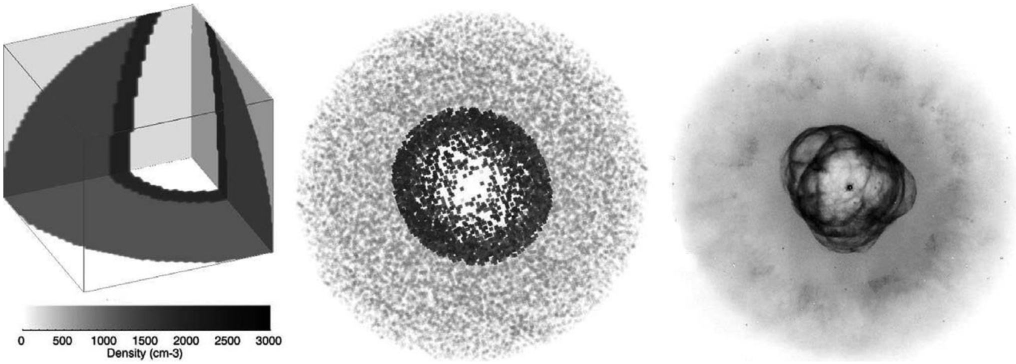


**Figure 1.** (Left) Cross-section of the density distribution used for NGC 2392. (Right) Computed surface brightness of NGC 2392 in [O III] $\lambda$5007 compared with the *HST* image.

While various shock models can roughly reproduce the [Ne V] flux, they fail to reproduce the ionization structure of the other lines. Our photoionization model predictions generally agree with the observations, adopting a volume filling factor of 0.07 (see Boffi & Stanghellini 1994). We note that Guerrero *et al.* (2011) have discovered a very hard X-ray source coincident with the CSPN. If the stars form a close binary (see Méndez *et al.* 2011), it is possible that the X-rays are produced from accretion of material on to the companion. The high effective temperature could also be explained by re-heating of this star. We also estimate the stellar masses from evolutionary tracks. The WD mass is $\approx 1\,M_{\odot}$, and the total mass is $\approx 1.6\,M_{\odot}$, which exceeds the Chandrasekhar limit. Hence, the system is a potential Type Ia SN progenitor. Further observations are needed to better understand the nature of this very interesting system.

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