ANALYSIS OF CO-SPATIAL UV-OPTICAL $HST$/STIS SPECTRA OF PLANETARY NEBULA NGC 3242

TIMOTHY R. MILLER, RICHARD B. C. HENRY, BRUCE BALICK, KAREN B. KWITTER, REGINALD J. DUFOUR, RICHARD A. SHAW, AND ROMANO L. M. CORRADI

1 Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA
2 Department of Astronomy, University of Washington, Seattle, WA 98195, USA
3 Department of Astronomy, Williams College, Williamstown, MA 01267, USA
4 Department of Physics and Astronomy, Rice University, Houston, TX 77251, USA
5 National Optical Astronomy Observatory, Tucson, AZ 85719, USA
6 Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain
7 Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain

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ABSTRACT

This project sought to consider two important aspects of the planetary nebula NGC 3242 using new long-slit $HST$/STIS spectra. First, we investigated whether this object is chemically homogeneous by spatially dividing the slit into different regions and calculating the abundances of each region. The major result is that the elements of He, C, O, and Ne are chemically homogeneous within uncertainties across the regions probed, implying that the stellar outflow was well-mixed. Second, we constrained the stellar properties using photoionization models computed by CLOUDY and tested the effects of three different density profiles on these parameters. The three profiles tested were a constant density profile, a Gaussian density profile, and a Gaussian with a power-law density profile. The temperature and luminosity were not affected significantly by the choice of density structure. The values for the stellar temperature and luminosity from our best-fit model are $89.7^{+7.3}_{-4.1}$ kK and $\log(L/L_{\odot}) = 3.36^{+0.22}_{-0.22}$, respectively. Comparing to evolutionary models on an HR diagram, this corresponds to an initial and final mass of $0.95^{+0.35}_{-0.65} M_\odot$ and $0.56^{+0.01}_{-0.01} M_\odot$, respectively.

Key words: galaxies: abundances – ISM: abundances – planetary nebulae: general – planetary nebulae: individual (NGC 3242) – stars: evolution – stars: fundamental parameters

1. INTRODUCTION

Understanding the chemical distribution within the ejected matter that creates a planetary nebula is important for determining a stellar evolution model that accurately describes the progenitor star. Knowing this evolution allows for the proper calculation of stellar yields of elements ejected into the interstellar medium. The ideal candidate to use in a search for spatial variations in the chemical composition is one that has a high surface brightness and is easily resolvable. NGC 3242 is one such planetary nebula. It is bright and extended on the sky, which allows for a detailed comparison at different locations in the nebula of many observed line strengths with their model-predicted values. It also exhibits a multi-shell structure. The brightest features include an inner $28'' \times 20''$ shell surrounded by a $46'' \times 40''$ halo (Ruiz et al. 2011). Thus, the possibility exists that the chemical composition varies from the shell to the halo or from one side of the planetary nebula to the other. This can arise if the halo and shell resulted from mass-loss events occurring at significantly different times during the evolution of the progenitor star or the outflows themselves were inhomogeneous. For stars around 1 solar mass, carbon will be enriched in their nebulae and thus is a prime element to look at in NGC 3242. The main goal of this paper (third in the series) is to use spatially resolved $Hubble Space Telescope (HST)/STIS$ spectra presented in Dufour et al. (2015, hereafter Paper I) to search for positional variations in the abundances of carbon, oxygen, neon, and helium relative to hydrogen and one another.

Numerous authors have studied the chemical composition of NGC 3242 over the last two decades. Krabbe & Copetti (2006) made long-slit observations in the optical and calculated the abundances for He, O, N, Ne, S, and Cl. The long-slit spectra of Milingo et al. (2002) and the fiber-fed observations of Monteiro et al. (2013) covered both optical and near-infrared wavelengths. Milingo et al. (2002) calculated abundances for the above six elements plus argon while Monteiro et al. (2013) reported all of the elements of Milingo et al. (2002) except neon. Both Henry et al. (2000) and Tsamis et al. (2003) combined archived $IUE$ ultraviolet data with ground-based optical to near-infrared long-slit data. The ultraviolet data enabled them to add carbon to the list of elemental abundances for NGC 3242.

Out of all of these authors, only Monteiro et al. (2013) addressed the idea of chemical inhomogeneity in NGC 3242. They observed the nebula between 3900 and 7000 Å using 6400 fibers on board the instrument VIMOS-IFU, covering an area of $54'' \times 54''$. They measured accurate oxygen and helium abundances from the most abundant ionic species in this range. For other elements in the study, i.e., nitrogen, sulfur, and chlorine, only less abundant ionic species were observable, resulting in large (as high as six times) discrepancies in the total abundances measured at different locations in the nebula. Monteiro et al. (2013) concluded that helium and oxygen were homogeneous throughout NGC 3242. Carbon was not part of that study, unlike in the current paper, since collisionally excited lines of carbon appear only in the ultraviolet.

In addition to the abundance characteristics of NGC 3242, its central star has been studied using many different techniques by numerous authors, e.g., Frew (2008), Pauldrach et al. (2004), and Henry et al. (2015, hereafter Paper II), resulting in...
a broad range of derived effective temperatures (60–95 kK) and luminosities \( \log(L/L_\odot) = 2.86–4.01 \). Therefore, the second goal of this paper is to better constrain the stellar properties of NGC 3242 through the use of photoionization modeling with the nebular emission lines as constraints.

We discuss the extraction of the spectra and observational results in Section 2. Section 3 contains the modeling and model results followed by the discussion of these in Section 4. We finish with a summary and conclusions in Section 5.

2. SPECTRAL EXTRACTION AND OBSERVATIONAL RESULTS

A complete description of the observations pertaining to this project can be found in Paper I. To summarize, the spectra used here are part of the observations from the GO12600 spectra cycle 19 program, which is unique in that it consists of co-spatial HST/STIS spectra covering the entire UV-optical-near-IR range from 1150 to 10,270 Å at 0.02Å resolution. Extraction of spectra from this data was accomplished by running an in-home Python script, which followed the prescriptions in the STIS Data Handbook. The versatility of the script allowed for the division of long-slit observations into smaller regions along the spatial direction. Thus, the signal-to-noise ratio in account to maximize the number of emission lines measured, a total of nine regions were chosen, each 2″2 × 0″2. Our analysis also included consideration of the full region spanning the nine smaller regions. The full region is shown in Figure 1 as a green rectangle outlining the nine smaller regions that appear as red filled, green rectangles. Almost all the fluxes of the emission lines were measured in each region using the IRAF8 task splot by fitting Gaussian profiles. Those that were not, specifically the carbon lines λ1909 and λ1907, were measured by summing the observed flux since those lines originate from an M-grating and exhibit flat-topped emission features. As a check for an over-estimation of any one line strength, the summed fluxes from the nine regions had to agree with that of the full region in order for the measurements to be included for further analysis. The uncertainty estimate for each line was calculated from the measured continuum rms noise nearby and the line’s FWHM.

8 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

Tables 1 and 2 show our measured and dereddened line intensities by region. The first two columns show the wavelength in Å of the emission line and line identification by ion, respectively. The value of the reddening function at each wavelength, \( f(\lambda) \), is shown in the third column. Each pair of columns labeled \( F(\lambda) \) and \( I(\lambda) \) that follows lists the observed and dereddened (with uncertainty) line strengths, respectively, where all values are normalized to \( F(H\beta) \) or \( I(H\beta) = 100 \). At the end of each \( F(\lambda) \) column, we list the logarithmic reddening parameter, \( c \), the theoretical ratio of \( F(H\alpha/H\beta) \), and the observed flux of \( H\beta \) in erg cm\(^{-2}\) s\(^{-1}\). The values for \( F(H\alpha/H\beta) \) were calculated using the relevant nebular temperature and density in an iterative loop. The values of \( c \) are very consistent (rms = 0.01) among the regions and the small differences that are present have negligible effects on the final line strengths and abundances. This argues against the presence of spatially dependent internal reddening.

Nebular temperatures, densities, and abundances with errors were calculated from the emission line measurements using the program Emission Line Spectrum Analyzer (ELSA; Johnson et al. 2006). ELSA corrected for interstellar extinction using the function prescribed by Savage & Mathis (1979) for optical wavelengths and by Seaton (1979) for the ultraviolet wavelengths. Corrections were also made for the contamination caused by He\(^{++}\) recombination lines to the first four hydrogen Balmer lines. Ionic abundance calculations were carried out using a five-level atom scheme. The propagated uncertainties took into account the input line strength uncertainties as well as the resulting uncertainties in temperature, density, and logarithmic extinction. Finally, ionization correction factors (ICFs) were calculated by ELSA using the prescriptions outlined in Kwitter & Henry (2001) and Paper I. These ICFs were then applied to the sum of the observed ionic abundances of all elements except carbon to produce elemental abundances. For carbon, the total abundance was taken as the direct sum of the ionic abundances since it was shown in Paper I to be more accurate.

The ionic abundances and ICF for each observed element are listed in Tables 3 and 4. The first column lists the ionic species (and wavelength of emission lines in Å) that relate to values in succeeding columns. The remaining columns contain the ionic abundances for the individual regions. The ICF for each element is listed by region below the ionic abundances. Finally, the two bottom rows of Tables 3 and 4 provide inferred values of [O III] temperature and C III] density. The necessary lines for determining the [S II] density and [N II] temperature were too weak to enable reliable values to be calculated.

Table 5 contains the elemental abundances of helium, carbon, oxygen, and neon for each region. The first column in Table 5 lists the abundance relative to hydrogen plus the ratios of C/O and Ne/O. The remaining columns contain the abundance ratios for each region. For reference, the solar values are shown in the last column (Asplund et al. 2009). A comparison by region of each element is shown in Figure 2. Comparison points from Henry et al. (2000) and Milingko et al. (2002) are also plotted. As can be seen, all of the regional abundances in each panel agree within the errors. Comparing the abundances of our full region to those in Milingko et al. (2002), all abundances are in agreement, while the helium and oxygen abundances are higher than the values of Henry et al. (2000).
Table 1
Fluxes and Intensities

| Wave (Å) | ID | Region Full | Region 1 | Region 2 | Region 3 | Region 4 |
|----------|----|-------------|----------|----------|----------|----------|
|          |    | $f(\lambda)$ | $F(\lambda)$ | $I(\lambda)$ | $F(\lambda)$ | $I(\lambda)$ | $F(\lambda)$ | $I(\lambda)$ | $F(\lambda)$ | $I(\lambda)$ |
| 1485     | N IV | 1.231 | 8.47 | 10.1 ± 0.86 | 2.24 | 2.66 ± 0.92 | 7.06 | 8.41 ± 1.43 | 11.2 | 12.3 ± 1.89 | 7.73 | 9.80 ± 1.88 |
| 1907     | C III | 1.226 | 121 | 144 ± 5 | 117 | 138 ± 27 | 118 | 141 ± 12 | 130 | 143 ± 15 | 129 | 163 ± 21 |
| 1909     | C III | 1.229 | 88.8 | 106 ± 4 | 80.8 | 95.6 ± 19.07 | 91.3 | 109 ± 9 | 92.7 | 102 ± 11 | 92.5 | 117 ± 16 |
| 3727$^a$ | [O II] | 0.292 | 4.38 | 4.57 ± 1.85 | ... | ... | ... | ... | ... | ... | ... |
| 3869     | [Ne III] | 0.252 | 96.6 | 100 ± 2 | 106 | 110 ± 9 | 101 | 105 ± 7 | 90.8 | 92.7 ± 5.26 | 105 | 110 ± 7 |
| 3969     | [Ne III] | 0.224 | 28.7 | 29.6 ± 1.64 | 31.9 | 32.9 ± 5.08 | 29.1 | 30.1 ± 2.93 | 24.8 | 25.2 ± 2.95 | 32.5 | 33.9 ± 4.36 |
| 4340     | Hβ   | 0.188 | 26.8 | 27.6 ± 1.70 | 28.9 | 29.7 ± 4.23 | 28.1 | 28.9 ± 2.20 | 25.7 | 26.1 ± 3.72 | 29.7 | 30.8 ± 4.29 |
| 4363     | O III | 0.118 | 12.8 | 13.0 ± 0.96 | 12.8 | 13.0 ± 4.58 | 14.1 | 14.4 ± 1.33 | 12.7 | 12.9 ± 2.20 | 15.2 | 15.6 ± 2.97 |
| 4868     | He II | 0.036 | 47.4 | 47.6 ± 0.73 | 18.6 | 18.7 ± 3.90 | 41.1 | 41.3 ± 2.99 | 55.8 | 56.0 ± 2.49 | 36.6 | 36.9 ± 3.97 |
| 4861     | Hβ   | 0.000 | 100 | 100 ± 0 | 100 | 100 ± 0 | 100 | 100 ± 0 | 100 | 100 ± 0 | 100 | 100 ± 0 |
| 4959     | [O III] | −0.030 | 414 | 412 ± 3 | 459 | 457 ± 19 | 441 | 439 ± 8 | 369 | 368 ± 8 | 448 | 446 ± 12 |
| 5007     | [O III] | −0.042 | 1233 | 1225 ± 8 | 1367 | 1359 ± 53 | 1313 | 1305 ± 22 | 1098 | 1095 ± 22 | 1336 | 1326 ± 34 |
| 5876     | He I  | −0.231 | 9.71 | 9.39 ± 0.66 | 15.3 | 14.8 ± 3.44 | 13.0 | 12.6 ± 2.41 | 9.15 | 8.98 ± 3.38 | 10.4 | 9.98 ± 3.82 |
| 6563     | Hα   | −0.360 | 297 | 282 ± 0 | 298 | 283 ± 2 | 297 | 282 ± 1 | 290 | 282 ± 1 | 302 | 282 ± 1 |
| 6678$^a$ | He I  | −0.380 | 2.28 | 2.16 ± 0.48 | ... | ... | ... | ... | ... | ... | ... |
| 7136$^a$ | [Ar III] | −0.453 | 6.83 | 6.39 ± 0.68 | ... | ... | ... | ... | ... | ... | ... |
| 9532$^a$ | [S III] | −0.632 | 10.6 | 9.67 ± 1.91 | ... | ... | ... | ... | ... | ... | ... |

Notes.

$^a$ This line was reliably measured for Region Full only.

$^b$ Logarithmic extinction at Hβ.

$^c$ Expected intrinsic Hα/Hβ ratio at nebular temperature and density.

$^d$ erg cm$^{-2}$ s$^{-1}$ in our extracted spectra.
| Wave | ID | Region 5 | Region 6 | Region 7 | Region 8 | Region 9 |
|------|----|----------|----------|----------|----------|----------|
| Å    |    | (f(λ)) | (F(λ))   | (I(λ))   | (F(λ))   | (I(λ))   |
|      |    |         |          |          |          |          |
| 1485 | N IV | 1.231   | 10.2 ± 2.04 | 8.85 ± 1.1 | 11.6 ± 1.7 | 7.47 ± 1.9 |
| 1907 | C III | 1.226   | 150 ± 18 | 123 ± 154 | 114 ± 141 | 120 ± 147 |
| 1909 | C III | 1.299   | 110 ± 14 | 90.0 ± 113 | 91.7 ± 114 | 88.7 ± 102 |
| 3869 | [Ne III] | 0.252   | 101 ± 6 | 103 ± 108 | 92.0 ± 96.2 | 93.9 ± 96.8 |
| 3969 | [Ne III] | 0.224   | 29.7 ± 3.34 | 31.1 ± 32.4 | 25.4 ± 26.4 | 27.5 ± 28.3 |
| 4101 | Hδ | 0.188   | 24.6 ± 3.39 | 25.5 ± 26.4 | 24.3 ± 25.2 | 26.1 ± 26.7 |
| 4340 | Hγ | 0.124   | 44.4 ± 3.46 | 46.1 ± 47.2 | 44.3 ± 45.3 | 47.2 ± 47.9 |
| 4363 | [O III] | 0.118   | 12.9 ± 3.23 | 13.3 ± 13.6 | 12.5 ± 12.8 | 14.2 ± 14.4 |
| 4686 | He II | 0.036   | 47.9 ± 3.26 | 47.5 ± 47.9 | 52.4 ± 52.7 | 68.5 ± 68.8 |
| 4861 | Hβ | 0.000   | 100 ± 0 | 100 ± 100 | 100 ± 100 | 100 ± 100 |
| 4959 | [O III] | −0.030  | 418 ± 10 | 422 ± 420 | 396 ± 394 | 364 ± 363 |
| 5007 | [O III] | −0.042  | 1242 ± 29 | 1258 ± 1248 | 1179 ± 1171 | 1086 ± 1080 |
| 5876 | He I | −0.231  | 7.72 ± 2.37 | 7.64 ± 7.32 | 7.75 ± 7.44 | 5.66 ± 5.5 |
| 6563 | Hα | −0.360  | 282 ± 2 | 302 ± 282 | 300 ± 282 | 293 ± 281 |

\[ \begin{align*}
\text{Notes.} & \\
& \text{a Logarithmic extinction at Hβ.} \\
& \text{b Expected intrinsic Hα/Hβ ratio at nebular temperature and density.} \\
& \text{c erg cm}^{-2} \text{s}^{-1} \text{in our extracted spectra.}
\end{align*} \]
along each respective line of sight, regions 2 and 7 have the
errors with the 11,700 K value of the full region. Also, the right

\[ n \text{ cm}^{-3} \]

Note.

\[ ^a \text{ Abundances relative to } H^+; \text{n.n.m } n.n.m(-k)=n(n.m) \times 10^{-4}. \]

Table 3

| Ion     | Region Full | Region 1 | Region 2 | Region 3 | Region 4 |
|---------|-------------|----------|----------|----------|----------|
| He\(^+\)(5876) | 6.25 ± 0.45(−2) | 0.106 ± 0.026 | 8.10 ± 1.56(−2) | 5.99 ± 2.27(−2) | 6.61 ± 2.55(−2) |
| He\(^+\)(4686) | 4.40 ± 0.07(−2) | 1.73 ± 0.36(−2) | 3.82 ± 0.28(−2) | 5.16 ± 0.23(−2) | 3.40 ± 0.37(−2) |
| icf(He) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| O\(^+\)(3727) | 2.23 ± 0.90(−6) | ... | ... | ... | ... |
| O\(^+\)(5007) | 2.58 ± 0.21(−4) | 3.17 ± 1.21(−4) | 2.67 ± 0.27(−4) | 2.04 ± 0.40(−4) | 2.48 ± 0.53(−4) |
| O\(^+\)(4959) | 2.59 ± 0.21(−4) | 3.18 ± 1.22(−4) | 2.68 ± 0.27(−4) | 2.05 ± 0.40(−4) | 2.48 ± 0.54(−4) |
| O\(^+\)(4363) | 2.58 ± 0.21(−4) | 3.17 ± 1.21(−4) | 2.67 ± 0.27(−4) | 2.04 ± 0.40(−4) | 2.48 ± 0.53(−4) |
| O\(^+\)(adopt) | 2.59 ± 0.21(−4) | 3.17 ± 1.21(−4) | 2.67 ± 0.27(−4) | 2.04 ± 0.40(−4) | 2.48 ± 0.53(−4) |
| icf(O) | 1.70 ± 0.05 | 1.16 ± 0.05 | 1.47 ± 0.10 | 1.86 ± 0.33 | 1.52 ± 0.2 |
| C\(^+\)(3235) | 3.72 ± 0.28(−7) | 3.20 ± 1.09(−7) | 3.43 ± 0.66(−7) | 3.50 ± 0.70(−7) | 4.26 ± 1.19(−7) |
| C\(^+\)(1909) | 2.01 ± 0.35(−4) | 2.35 ± 1.96(−4) | 1.87 ± 0.42(−4) | 1.51 ± 0.62(−4) | 1.73 ± 0.80(−4) |
| C\(^+\)(1907) | 2.01 ± 0.35(−4) | 2.35 ± 1.96(−4) | 1.87 ± 0.42(−4) | 1.51 ± 0.62(−4) | 1.73 ± 0.80(−4) |
| C\(^+\)(adopt) | 2.01 ± 0.35(−4) | 2.35 ± 1.96(−4) | 1.87 ± 0.42(−4) | 1.51 ± 0.62(−4) | 1.73 ± 0.80(−4) |
| C\(^+\)(1549) | 3.12 ± 0.67(−5) | 3.08 ± 3.14(−5) | 3.76 ± 0.90(−5) | 2.54 ± 1.27(−5) | 2.09 ± 1.17(−5) |
| Ne\(^+\)(3869) | 5.60 ± 0.53(−5) | 6.89 ± 3.06(−5) | 5.65 ± 0.75(−5) | 4.50 ± 1.02(−5) | 5.36 ± 1.34(−5) |
| Ne\(^+\)(1575) | 3.52 ± 0.45(−5) | 2.66 ± 1.61(−5) | 4.23 ± 0.99(−5) | 2.40 ± 0.75(−5) | 2.63 ± 1.20(−5) |
| icf(Ne) | 1.72 ± 0.05 | 1.16 ± 0.05 | 1.47 ± 0.10 | 1.86 ± 0.33 | 1.52 ± 0.2 |
| [O III] \( T_e \) (K) | 11700 ± 300 | 11400 ± 1400 | 11900 ± 400 | 12200 ± 800 | 12200 ± 800 |
| C III] \( N_e \) (cm\(^{-3}\)) | 4500 ± 300 | 1800 ± 1700 | 7000 ± 900 | 3300 ± 1000 | 3700 ± 1400 |

Note.

\[ ^a \text{ Abundances relative to } H^+; \text{n.n.m } n.n.m(-k)=n(n.m) \times 10^{-4}. \]

Similarly, Figure 3 shows the comparison of each region’s
[O III] temperature and C III] density. Values from Henry et al.
(2000) and Milingo et al. (2002) are again shown for comparison.
As can be seen in the left panel and at the ends of
Tables 3 and 4, the [O III] electron temperatures of the
regions range from 11,400–12,300 K but are consistent within
errors with the 11,700 K value of the full region. Also, the right
panel of Figure 3 and the ends of Tables 3 and 4 show that
along each respective line of sight, regions 2 and 7 have the
largest electron densities at 7000 cm\(^{-3}\) and 9000 cm\(^{-3}\),
respectively, while regions 3–6 and 8 are within the errors of
the full region’s value of 4500 cm\(^{-3}\). Regions 1 and 9 show the
smallest densities of 1800 cm\(^{-3}\) and 1500 cm\(^{-3}\), respectively.
The density observed in region 7 appears to be unusually high
compared to the much brighter region 2, assuming that the
brightness is proportional to the density squared. A plausible
explanation is that there is a small knot of enhanced density
that is emitting the observed light, though a literature search
turns up no corroboration.

3. MODELING AND MODEL RESULTS

Photoionization models of NGC 3242 were computed in order
to constrain the central star temperature and luminosity
using CLOUDY version 13.03 (Ferland et al. 2013). During the
computational process, CLOUDY steps outward from the center of the nebula, solving the energy balance and ionization balance equations simultaneously at every point. Three iterations of this process were performed to ensure a steady-state solution for the resulting model. Each model employed a Rauch H–Ni stellar atmosphere simulation for the central star spectral energy distribution (Rauch 2003). The Rauch models include line blanketing of all elements on the periodic table, spherical symmetry, and no shock heating of the gas. Additional assumptions included a distance to NGC 3242 of 1 kpc and an initial central star temperature and luminosity of 89,000 K and 3450 $L_\odot$, respectively (Frew 2008; Frew et al. 2016). Finally, the inferred nebular density and abundances from Section 2 were used as initial input into the photoionization models of each region.

Model line-of-sight line strengths for the emission lines in Tables 1 and 2 were calculated using an in-home C++ program called the PLANetary Nebula Intensity Calculator (PANIC). PANIC used model-generated radial emissivity values paired with their radial distances from the central star to compute each emission line strength. Specifically, PANIC calculated the volume of gas intersected by each region for each radial distance from the model, multiplied it by the appropriate emissivity, and then added up each contribution to determine the total emission for every line. This line emission was then multiplied by the filling factor (the ratio of volume filled by gas to total volume) to account for the clumpiness of the gas in the model. Of the modeled emission lines, at least seven were used to compare with observed line intensities, typically the strongest line for each ion. This ensures equal weighting among ions. Furthermore, values for up to five diagnostics9, which are particularly sensitive to nebular properties or the central star’s temperature and luminosity, were calculated in order to help break the degeneracy among models whose predicted line strengths otherwise closely matched the observed line strengths.

The agreement between model-generated and observed line strengths and diagnostic values was evaluated by calculating a total rms via the expression $\sqrt{\frac{1}{N}\sum_{i=1}^{N}(\text{model}_i - \text{observed}_i)^2}$, where $N$ is the total number of lines and diagnostics (15 for Region Full). The diagnostics included also act as a weighting system for the more important lines. Similarly, the total rms for observed line strengths and diagnostics was calculated by substituting the uncertainty in place of the model value. This observed rms was used to assess error estimates on input parameters described later.

To test the validity of the described rms method for assessing the best model, we also used the method of Morisset & Georgiev (2009). In their method, a quality factor, $Q$, is calculated by the expression $\frac{\log(\text{model}) - \log(1 + \text{RelativeError})}{\text{uncertainty} \text{observed}}$, where RelativeError is the uncertainty estimated for each measured line. Minimizing this $Q$ value instead of the rms resulted in a small difference in the best-fit stellar temperature and luminosity of only 200 K and 0.011 dex, respectively.

Three different density profiles were tested during our analysis: a constant profile, a Gaussian profile, and a Gaussian with a power-law profile. The constant density profile has a defined inner and outer radius and a single density throughout the gas. However, it is likely to be the least appropriate profile of the three, given the multi-shell structure of NGC 3242 and the rigid boundary conditions. The Gaussian profile, on the other hand, relaxes the sharp boundary cutoff and constant density condition. However, a simple Gaussian profile still does not account for the outer shell. Thus, we added a radially decreasing power-law profile to the previous Gaussian profile to simulate it. All three profiles were used to test the dependence of the stellar parameters upon the choice of density profile. Figure 4 illustrates the different profiles.

Since each model assumes a specific value for each stellar and nebular parameter, locating the global minimum (in parameter space) or best value for each stellar parameter was helped by computing a suite of constant density models spanning a wide range of stellar and nebular parameters, using resources from the OU Supercomputing Center for Education and Research at the University of Oklahoma. To minimize the number of models required to cover the relevant parameter space, we used the

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9 $\lambda$\text{O III}]\lambda5007+$\lambda$4959+\lambda3727]/H$\beta$, (\text{O II}]\lambda3727)/(\text{O III}]\lambda5007), (\text{He II}\lambda4686)/(\text{He I}\lambda5876), (\text{O III}]\lambda4363$\lambda$5007), and C III]\lambda1909/$\lambda$1907

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Table 5

| Parameter          | Full Region | Region 1 | Region 2 | Region 3 | Region 4 | Solar |
|--------------------|-------------|----------|----------|----------|----------|-------|
| He/H ($10^{-2}$)  | 10.60$^{+0.50}_{-0.50}$ | 12.30$^{+2.60}_{-2.60}$ | 11.90$^{+1.60}_{-1.60}$ | 11.1$^{+2.3}_{-2.3}$ | 10.0$^{+2.5}_{-2.5}$ | 8.51   |
| C/H ($10^{-4}$)    | 2.32$^{+0.36}_{-0.36}$ | 2.66$^{+1.98}_{-1.98}$ | 2.21$^{+1.98}_{-1.98}$ | 1.76$^{+0.63}_{-0.63}$ | 1.94$^{+0.80}_{-0.80}$ | 2.69   |
| C/O                | 0.52$^{+0.09}_{-0.09}$ | 0.72$^{+0.062}_{-0.062}$ | 0.56$^{+0.127}_{-0.127}$ | 0.46$^{+0.203}_{-0.203}$ | 0.51$^{+0.248}_{-0.248}$ | 0.550  |
| O/H ($10^{-4}$)    | 4.44$^{+0.36}_{-0.36}$ | 4.10$^{+0.355}_{-0.355}$ | 3.93$^{+0.45}_{-0.45}$ | 3.80$^{+0.96}_{-0.96}$ | 3.75$^{+0.92}_{-0.92}$ | 4.90   |
| Ne/H ($10^{-5}$)   | 9.62$^{+0.91}_{-0.91}$ | 8.02$^{+3.55}_{-3.55}$ | 8.31$^{+2.20}_{-2.20}$ | 8.37$^{+0.31}_{-0.31}$ | 8.12$^{+2.23}_{-2.23}$ | 8.51   |
| Ne/O               | 0.217$^{+0.004}_{-0.004}$ | 0.217$^{+0.016}_{-0.016}$ | 0.217$^{+0.016}_{-0.016}$ | 0.220$^{+0.002}_{-0.002}$ | 0.216$^{+0.011}_{-0.011}$ | 0.174  |

Note.

a Asplund et al. (2009).
following method of analysis. A primary grid of 81,000 models was produced by varying the stellar temperature and luminosity, the inner and outer radii, and the filling factor of the gas while holding the abundances of He, C, Ne, and O constant. The range of the stellar temperature and luminosity was between 50,000 and 100,000 K \((\Delta T = 1000 \, K)\) and \((\log(L/L_{\odot}) = 3.0–5.0 \, (\Delta \text{dex} = 0.1)\), respectively. These ranges cover all published values of these stellar parameters. The filling factor was varied between 0.01 and 0.5, a range that encompasses typical values of planetary nebulae, in steps of 0.01. The inner/outer radius were varied from 0.039 pc/0.0415 pc to 0.041 pc/0.0437 pc with a step size of \(10^{-3} \, \text{pc}/10^{-4} \, \text{pc}\), covering values that are reasonable for the assumed distance. The nebular composition was chosen to be the full region’s value from Table 5, since all regions had elemental abundances within the errors of the full region’s values. Grains were chosen to be the planetary nebula set internal to CLOUDY with a fixed scaling factor of 1.0. The density was chosen to be the full region’s value of 4500 cm\(^{-3}\) except for Regions 1, 2, 7, and 9.

Next, the set of observed emission line strengths for NGC 3242 were used to reduce the primary grid to a smaller group of models, which were the most successful at reproducing the observations, as determined by the previously discussed rms analysis. Finally, the abundances were varied within the observed errors to produce a secondary grid of over 10 million models to further reduce the model rms. Ultimately, the best values were found by starting with the best model from the grid, and manually adjusting each input parameter and keeping the values that lowered the model rms. An estimation of the error for each parameter was carried out by starting with the best model and varying each parameter one at a time (the stellar temperature and luminosity were varied together) until the model rms was larger than the sum of the best-fit model rms and observed rms\(^{10}\), e.g., model rms > 0.21 for Region Full. This estimation process was used only for the constant density.

\(^{10}\) Admittedly, each parameter is not fully independent. However, varying the stellar parameters together takes into account more of the covariance.
models, due to constraints imposed by computational time requirements.

Tables 6 and 7 show how well the best constant density models for each region were able to match the observed emission line strengths. The first two columns are the wavelength and ion line identification, respectively. The next five columns separate the regions with the ratio of the model emission line strength to the observed emission line strength. Region Full has the most lines that are outside the errors listed in Tables 1 and 2. This is probably due to the modeling assumptions becoming less valid compared to the smaller regions and the smaller uncertainties in the line strengths. Table 8 has the same format as the previous two tables but shows the Gaussian and Gaussian with the power-law density profile models of only Region Full. These models are able to match the observed emission lines about as well as the constant density model.

The parameters for the best-fit constant density models for each region, along with their estimated errors, are shown in Tables 9 and 10. The dust scaling factor was set to 0.077 for these models. The first column lists the stellar and nebular parameters. Only the parameters with associated errors were varied. Near the bottom, we provide the electron temperature/density and ICFs for oxygen and neon from the model. The total rms for both the model and the observation are also given.

As can be seen, the model rms is smaller than the observed rms for all regions. The smaller the model rms, the better the model was able to match the emission lines and diagnostics for each region. For example, the smallest model rms of 1.63 from region 4 implies that the assumptions that went into the model were more representative of the true physical structure of this region. The models reproduced the observed temperatures and densities within their respective errors in all cases. The model ionization correction factors are smaller than their observed counterparts given in Tables 3 and 4 in all regions except region 1, with regions 7 and 8 having the largest differences.

The asymmetry in the errors is due to the $1 - \frac{\text{model}}{\text{observed}}$ term in the equation for the rms having a lower bound of one. The errors in stellar temperature and luminosity and nebular abundances are inversely related to overall signal strength in the emission lines, where the larger error corresponds to overall weaker signal strength. Since the full region possesses the highest signal-to-noise ratio, we adopt its values of $89.7^{+3.7}_{-4.7}$ kK and $\log(L/L_{\odot}) = 3.36^{+0.28}_{-0.22}$ for the central star of NGC 3242. Also, the model abundances in Tables 9 and 10 agree within estimated error with the observed abundances in Table 5, though carbon is systematically higher and neon is systematically lower in all cases.

Table 11 shows the central star parameters for the best-fit models of the Gaussian and Gaussian with a power-law density profiles along with the abundances and filling factor. The electron temperature and density, oxygen, and neon ICFs, and associated model rms are at the bottom. The first column identifies the nebular density profile, while the second column indicates the model parameters. The remaining column shows...
the value of each parameter for Region Full. The largest change in temperature and luminosity between the constant (Table 9) and non-constant (Table 11) density models is 1900 K and 0.1 dex, respectively, from the Gaussian density profile. The Gaussian with a power-law density profile more closely matches the stellar parameters of the constant density profile and is more representative of the nebular structure. Thus, there appears to be only a minor difference between these models and the constant density models in terms of the luminosity and temperature of the central star when considering the nebula as a whole. Therefore, our adoption above for the central star parameters from the constant density models is reasonable. The filling factor, on the other hand, is much larger in both the Gaussian and Gaussian with a power-law density models when compared to the constant density models. Both these profiles reproduce nearly the same electron temperature/density and ICFs as the constant density profile.

4. DISCUSSION

One of our primary results is that our spatially resolved studies of various regions of NGC 3242 show no evidence of abundance variation for He, C, O, and Ne within our uncertainties (Figure 2 and Table 5). This result has been
Table 8  
Non-constant Density Model Emission Lines Compared to Observations For Region Full  

| Wave (Å) | ID | Gaussian Model/Observed | Gaussian with Power Law Model/Observed |
|---|---|---|---|
| 1485 | N IV | 0.996 | 0.996 |
| 1907 | C III | 1.096a | 1.105a |
| 1909 | C III | 1.099a | 1.107a |
| 3727 | [O II] | 0.948 | 0.901 |
| 3869 | [Ne III] | 1.045a | 1.016 |
| 3969 | [Ne III] | 1.064a | 1.034 |
| 4101 | Hδ | 0.883a | 0.908a |
| 4340 | Hγ | 0.940a | 0.967a |
| 4363 | [O III] | 1.133a | 1.176 |
| 4686 | He II | 0.904a | 0.933a |
| 4861 | Hβ | 0.918a | 0.944a |
| 4959 | [O III] | 1.094a | 1.120a |
| 5007 | [O III] | 1.108a | 1.134a |
| 5876 | He I | 0.916a | 0.951 |
| 6563 | Hα | 0.923a | 0.948a |
| 6678 | He I | 1.055 | 1.095 |
| 7136 | [Ar III] | 1.004 | 1.028 |
| 9532 | [S III] | 1.024 | 1.033 |

Note.  
a Modeled emission line intensity outside observed error bar.

Table 9  
Constant Density Models  

| Parameter | Region Full | Region 1 | Region 2 | Region 3 | Region 4 |
|---|---|---|---|---|---|
| $T_{\text{star}}$ (kK) | 89.7±1.1 | 89.7 | 89.7 | 89.7 | 89.7 |
| $L_{\text{star}}$ (log$L/L_{\odot}$) | 3.36±0.28 | 3.36 | 3.36 | 3.36 | 3.36 |
| $H_{\text{gas}}$ (log$H_{\text{density}}$) | 6.7±0.04 | 3.25±0.06 | 3.7±0.04 | 3.5±0.06 | 3.5±0.06 |
| Inner Radius (10^{-2} pc) | 1.86±0.74 | 2.04±0.36 | 3.33±0.12 | 2.52±0.48 | 1.96±0.74 |
| Outer Radius (10^{-2} pc) | 3.80±0.30 | 10.50±2.90 | 3.90±0.13 | 4.59±0.81 | 10.20±2.60 |
| Filling Factor (10^{-3}) | 4.36±0.14 | 4.39±0.31 | 4.80±0.01 | 5.93±0.77 | 1.56±0.54 |
| He/H (10^{-2}) | 10.45±0.34 | 11.5±0.34 | 11.02±0.11 | 10.30±0.13 | 9.57±0.22 |
| C/H (10^{-4}) | 5.81±0.42 | 8.75±0.90 | 3.67±0.25 | 5.01±0.46 | 10.0±0.03 |
| O/H (10^{-4}) | 4.70±0.31 | 4.26±0.30 | 3.76±0.84 | 3.76±0.84 | 4.21±0.58 |
| Ne/H (10^{-5}) | 7.40±0.23 | 7.76±0.37 | 6.40±0.24 | 6.19±0.30 | 6.90±0.04 |
| [O III] $\lambda$ 5007 | 7.50±0.23 | 6.40±0.24 | 6.19±0.30 | 6.90±0.04 | 11800 | 11100 | 11600 | 11800 | 11800 |
| C III] $\lambda$ 977 | 4600 | 1500 | 6800 | 3500 | 3600 |
| icf (O) | 1.57 | 1.13 | 1.22 | 1.56 | 1.51 |
| icf (Ne) | 1.24 | 1.00 | 1.03 | 1.18 | 1.18 |
| Model rms (10^{-5}) | 6.26 | 2.40 | 3.75 | 4.46 | 1.63 |
| Observed rms (10^{-5}) | 15.02 | 20.91 | 10.68 | 17.06 | 18.57 |

stellar evolution models computed by Renzini & Voli (1981) indicated that the mixing timescales of convection in the envelope are much shorter than the nuclear timescales. More recent modeling by Buell (1997) and private communication suggests that the mixing time frame is on the order of one year compared to the nuclear timescale of the order of 10^3 – 10^9 years. Our results confirm that elements such as $^{12}$C, $^{13}$C, and $^{14}$N that are formed during the AGB phase of NGC 3242 are mixed into the envelope at a faster rate than mass ejections occur.

Looking at the central star parameters, Table 12 compares our best-fit temperature and luminosity of the constant density models to values found in the literature of the last 25 years. Taking into account the uncertainty for both parameters in Table 9, our temperature and luminosity are consistent with the values from Frew (2008) and Paper II. Tinkler & Lamers (2002) has a consistent temperature but higher luminosity when compared to our results.

From our model-derived central star temperature and luminosity, we can estimate the initial and final masses along with the current radius for NGC 3242. Figure 5 is a theoretical H–R diagram with post-AGB evolutionary tracks from Vassiliadis & Wood (1994); red solid lines, Schoenberner (1983); blue dashed lines, and Bertolami (2016; green dashed and purple dash-dotted lines). The initial/final masses relative to the Sun can be seen at the right end of each track. The position of NGC 3242 is shown. We interpolated between evolutionary tracks and took the average of the models to obtain an initial and final mass of 0.56±0.02 $M_{\odot}$ and 0.56±0.01 $M_{\odot}$, respectively. This final mass corresponds to the peak of the distribution for white dwarf masses in the Milky Way shown by Liebert et al. (2005), 0.56$M_{\odot}$. It is also somewhat smaller than the average white dwarf mass, 0.64 $M_{\odot}$, found by Liebert et al. (2005) as well as the peak central star mass, 0.60 $M_{\odot}$, found by Zhang & Kwok (1993) in their sample. Finally, we calculated a central star radius of 0.20±0.05 $R_{\odot}$ using the Stefan–Boltzmann law.

We also estimated the main-sequence lifetime plus zero-age main-sequence age, luminosity, radius, temperature, and spectral type of NGC 3242 from the initial mass. Using the mass–luminosity relation, $L \approx 1.02 M^{3.92}$ in solar units from

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Demircan & Kahraman (1991), the main-sequence lifespans of the Sun, $T_{\odot} \approx M_{\odot}/L_{\odot} = 9.5$ Gyr, and the age of the Milky Way Galaxy, 13.2 Gyr, the initial luminosity and main-sequence lifespans are $0.84^{+1.18}_{-0.27} L_{\odot}$ and $10.7^{+2.5}_{-6.4}$ Gyr, respectively. This luminosity suggests a spectral type of G4, with a range of G7–F5 (based on the uncertainties). The radius was calculated with the mass–radius relation, $R \approx 1.06 M_{\odot}^{0.945}$, also from Demircan & Kahraman (1991) and was found to be $1.01^{+0.34}_{-0.09} R_{\odot}$. From the Stefan–Boltzmann law, the temperature was determined to be $5500^{+900}_{-300}$ K.

### Table 10
Constant Density Models

| Parameter        | Region 5 | Region 6 | Region 7 | Region 8 | Region 9 |
|------------------|----------|----------|----------|----------|----------|
| $T_{\text{star}}$ (kK) | 89.7     | 89.7     | 89.7     | 89.7     | 89.7     |
| $L_{\text{star}}$ (log[$L/L_{\odot}$]) | 3.36     | 3.36     | 3.36     | 3.36     | 3.36     |
| $H_{\text{gas}}$ (log[$H_{\text{density}}$]) | 3.60^{+0.05}_{-0.06} | 3.60^{+0.05}_{-0.06} | 3.90^{+0.04}_{-0.04} | 3.55^{+0.05}_{-0.06} | 3.25^{+0.06}_{-0.07} |
| Inner Radius ($10^{-2}$ pc) | 2.52^{+0.48}_{-0.32} | 1.88^{+0.52}_{-1.18} | 2.02^{+0.08}_{-0.12} | 2.93^{+0.22}_{-0.28} | 3.56^{+0.34}_{-0.56} |
| Outer Radius ($10^{-2}$ pc) | 4.21^{+0.69}_{-0.41} | 6.49^{+0.96}_{-1.31} | 2.52^{+0.08}_{-0.12} | 3.74^{+0.22}_{-0.28} | 8.40^{+1.50}_{-1.50} |
| Filling Factor (10^{-3}) | 3.77^{+0.13}_{-0.07} | 1.52^{+0.58}_{-0.42} | 4.53^{+0.87}_{-0.83} | 1.00^{+1.00}_{-0.27} | 4.34^{+1.34}_{-1.44} |
| He/H ($10^{-5}$) | 10.12^{+2.87}_{-2.09} | 9.20^{+3.32}_{-3.68} | 9.29^{+1.88}_{-2.29} | 7.69^{+3.56}_{-1.78} | 10.50^{+4.04}_{-2.51} |
| C/H ($10^{-5}$) | 6.30^{+3.99}_{-2.09} | 5.60^{+3.12}_{-2.68} | 4.47^{+2.65}_{-1.64} | 5.31^{+3.36}_{-1.94} | 4.81^{+3.15}_{-2.38} |
| O/H ($10^{-5}$) | 5.30^{+1.75}_{-2.65} | 5.08^{+1.84}_{-2.68} | 3.77^{+1.40}_{-1.64} | 3.30^{+1.35}_{-1.50} | 4.54^{+1.59}_{-1.50} |
| Ne/H ($10^{-5}$) | 7.93^{+3.54}_{-2.09} | 8.07^{+3.58}_{-2.68} | 5.85^{+3.32}_{-3.71} | 5.48^{+4.52}_{-2.10} | 7.38^{+4.42}_{-3.72} |

### Table 11
Non-constant Density Models for Region Full

| Parameter        | Gaussian | Gaussian with Power Law |
|------------------|----------|------------------------|
| $T_{\text{star}}$ (kK) | 91600 | 91200 |
| $L_{\text{star}}$ (log[$L/L_{\odot}$]) | 3.26 | 3.29 |
| Filling Factor (10^{-3}) | 9.77 | 9.83 |
| He/H ($10^{-5}$) | 9.84 | 9.93 |
| C/H ($10^{-5}$) | 5.28 | 5.21 |
| O/H ($10^{-5}$) | 4.54 | 4.46 |
| Ne/H ($10^{-5}$) | 7.11 | 6.61 |
| [O III] $T_{\text{star}}$ (K) | 11900 | 12000 |
| C III] $N_{\text{e}}$ (cm$^{-3}$) | 4700 | 4700 |
| icf (O) | 1.52 | 1.53 |
| icf (Ne) | 1.22 | 1.23 |
| rms ($10^{-2}$) | 7.88 | 8.61 |

### Table 12
Central Star Parameters Comparison

| Reference          | Temperature (kK) | Luminosity (log[$L/L_{\odot}$]) |
|--------------------|------------------|---------------------------------|
| This Work          | 89.7             | 3.36                            |
| Paper II           | 89.0             | 3.64                            |
| Frew (2008)        | 89.0             | 3.54                            |
| Pauldrach et al. (2004) | 75.0           | 3.51                            |
| Tinkler & Lamers (2002) | 94.5           | 3.75                            |
| Henry et al. (2000) | 60.0             | 4.30                            |
| Kudritzki et al. (1997) | 75.0           | 4.01                            |
| Acker et al. (1992) | 60.0             | 3.48                            |
The model-generated volume emissivities for each line were then input into the code PANIC, which converted the emissivities into line-of-sight line strengths. These lines as well as nebular diagnostics were then compared with their observed counterparts and an rms value, quantifying the closeness of the match, was used to choose the best-fit model and errors in each parameter. Lastly, we tested the effects of three different density profiles on the stellar parameters by using a constant, Gaussian, and Gaussian with a power-law profile for each region.

The following conclusions emerge from our work.

1. The inner shell and, with lesser confidence, the outer shell of NGC 3242 are chemically homogeneous, implying that the outflow from the star that produced the shells was well-mixed.

2. The constant density models constrain the stellar temperature and, to a lesser degree, the luminosity. Changing the density profile from a constant to the Gaussian or Gaussian with a power law resulted in a large increase in the filling factor but had a negligible effect on the inferred stellar properties. The Gaussian with a power-law profile was the most representative of the structure of NGC 3242 out of the three profiles tested here.

3. The progenitor mass of the central star of NGC 3242 was $0.95^{+0.35}_{-0.09}M_\odot$ when it formed 10.7$^{+2.3}_{-0.4}$ Gyr ago. It had a luminosity, temperature and radius of $0.84^{+1.29}_{-0.27}L_\odot$, 5500$^{+200}_{-300}$ K and 1.01$^{+0.34}_{-0.09}R_\odot$, respectively. Currently, the central star has a luminosity of $\log(L/L_\odot) = 3.36^{+0.28}_{-0.22}$ with a temperature of 89.7$^{+3.7}_{-4.7}$ KK and radius 0.20$^{+0.10}_{-0.07}R_\odot$.

In a follow-up paper (Paper IV: T. Miller et al. 2016, in preparation), we will analyze six additional objects, IC 2165, IC 3568, NGC 2440, NGC 5315, NGC 5882, and NGC 7662, as we did here in Paper III for NGC 3242.

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