THREE-DIMENSIONAL PHOTOIONIZATION STRUCTURE AND DISTANCES OF PLANETARY NEBULAE. I. NGC 6369

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ABSTRACT

We present the results of mapping the planetary nebula NGC 6369 by using multiple long-slit spectra taken with the Cerro Tololo Inter-American Observatory 1.5 m telescope. We create two-dimensional emission-line images from our spectra and use these to derive fluxes for 17 lines, the Hα/Hβ extinction map, the [S II] line ratio density map, and the [N II] temperature map of the nebula. We use our photoionization code constrained by these data to determine the distance and the ionizing star characteristics and to show that a clumpy hourglass shape is the most likely three-dimensional structure for NGC 6369. Note that our knowledge of the nebular structure eliminates all uncertainties associated with classical distance determinations, and our method can be applied to any spatially resolved emission-line nebula. We use the central star, nebular emission line, and optical+IR luminosities to show that NGC 6369 is matter bound, as about 70% of the Lyman continuum flux escapes. Using recent evolutionary tracks from Blöcker, we derive a central star mass of about 0.65 $M_\odot$.

Subject headings: planetary nebulae: individual (NGC 6369) — techniques: spectroscopic

1. INTRODUCTION

The planetary nebula (PN) NGC 6369, shown in Figure 1 in the light of Hα+[N II] 658.4 nm, is an object with a complex morphology, consisting of a main bright annulus of diameter 40′ and fainter, curved outer structures on two sides in the east-west direction. Deep narrowband Hα and [N II] 658.4 nm images of NGC 6369 were obtained by Corradi et al. (2003) in a survey to look for faint outer halos around PNs. Apart from being deeper, their image is not significantly different from the one shown in Figure 1, and no large faint halo was found.

The Hubble Space Telescope (HST) image of NGC 6369 also shows the same main features as our image but has additional resolved details and tags the Hα, [O II] 500.7 nm, and [N II] 658.4 nm lines with the colors red, blue, and green, respectively. In the section on observational results we discuss this composite HST image in more detail.

The equatorial and galactic coordinates for NGC 6369 are $\alpha = 17^h 29^m 20.40$, $\delta = 23^\circ 45' 37.9''$ (ICRS 2000), and $l = 2^\circ 43'$, $b = +5^\circ 85'$, respectively. The extreme distances determined for NGC 6369 are 0.33 kpc, obtained by Aannestad et al. (1984), and 2.00 kpc, obtained by Gathier et al. (1986), of a total of 10 listed by Acker et al. (1992), from which we obtain a mean value for the distance to NGC 6369 of 1039 ± 538 pc. Note that these 10 distances were determined using several statistical methods, each with its own systematic biases and assumptions, so the average probably is a reasonably unbiased estimator, within the (large) error.

The temperature of the central star obtained from the Zanstra method by Gathier & Pottasch (1989) is $T(H) = 67,600$ K. The star has been classified as a WC4 star by Tylenda et al. (1993).

Spectra of NGC 6369 were obtained by Acker et al. (1989) using an Image Dissector Scanner (IDS) as detector with double 4″ apertures, by Aller & Keyes (1987) using an Image Tube Scanner with a 2″ × 10″ slit, and by Perinotto et al. (1994) using an IDS and a combination of different apertures not bigger than 13″ × 13″. An expansion velocity of 41.5 km s$^{-1}$ has been determined by Meatheringham et al. (1988). The system radial velocity was reported to be −106 km s$^{-1}$ by Wilson (1953) and −101 km s$^{-1}$ by Meatheringham et al. (1988).

The spectral energy distribution (SED) of NGC 6369 is shown in Figure 2 and has been computed using flux values from Acker et al. (1992) and Schmeja & Kimeswenger (2002) over a range of wavelengths from 0.44 to 1100 μm. Note that we plot $F_{\lambda}$ against wavelength, and below we use the $F_{\lambda}$ values to determine the observed optical+IR luminosity of NGC 6369.

Planetary nebulae are generally classified according to their appearance, and such classification is then used for studies of the formation and evolution of these objects (e.g., Balick 1987). Such a classification, based on the observed two-dimensional brightness distribution in a given line or lines, can be quite misleading. This could be the case for NGC 6369, for which a round morphology is evident from the observed images. Different three-dimensional geometries can produce the same observed two-dimensional morphology as has been shown by Monteiro et al. (2000). Furthermore, images produced by ions of different ionization degree can be very different, because of the radiation transfer within the nebula. Only detailed modeling, which reproduces the brightness intensity distribution of different lines, as well other observed parameters, can provide more reliable information about the three-dimensional geometry of the gas distribution. The determination of the actual three-dimensional gas distribution in planetary nebulae is essential for understanding their formation and evolution, as well as that of the ionizing star.
By determining the three-dimensional structure of nebulae, we eliminate the large uncertainties that have plagued classical statistical distance determination methods for over five decades. Assumptions about the filling factor, constancy of ionized mass or diameter, mass-radius relationships, etc., are not needed here: we know what the structure and ionized mass are and can therefore determine distances to much greater accuracy than before. In this paper we explain in detail how we can determine this three-dimensional structure from long-slit spectra and our three-dimensional photoionization model, and we apply it to the case of NGC 6369.

In summary, we obtain the spatial structure of the object, along with its chemical composition, ionizing source temperature and luminosity, and mass, as well as an independent distance, in a self-consistent manner. In §2 we discuss the observations and basic reduction procedures, as well as the details of the image reconstruction technique used to obtain the line intensity maps. In §3 the results obtained from these maps are discussed: the reddening correction of the images, total line fluxes, and the computed temperature and density maps. In §4 we present the model results of the three-dimensional nebulae and click on “Optical Spectrographs,” then on “1.5 m RC spectrograph.”

2. OBSERVATIONS AND MAPPING

2.1. Observations and General Reduction

Observations were made using the Cerro Tololo Inter-American Observatory4 (CTIO) 1.5 m Ritchey-Chrétien telescope with the RC Spectrograph on the nights of 2002 June 12 and 13. We used a grating with 600 lines mm−1 blazed at 600 nm, giving a spectral resolution of 0.65 nm pixel−1 and a plate scale of 0′′.26 pixel−1.

Coverage obtained with this configuration was approximately 450–700 nm. We took three 1200 s exposures at each slit position for ease of cosmic hit removal, etc.5

By taking sets of exposures at several parallel long-slit positions across the nebula, we obtained line intensity profiles for each slit. These profiles were then combined to create emission-line images of the nebula with a spatial resolution of about 4″ × 4″, in a way similar to radio mapping. This method has been applied before for the PN NGC 3132 as discussed in Monteiro et al. (2002). A total of 10 positions were observed, moving the slit in 4″ steps in the north-south direction between exposures. The third position observed from south to north (east is to the left, and north is up in all the figures) was not observed because of pointing problems. For this position an average of the two adjacent exposures was adopted.

The seeing conditions during the observing run were 1.5 or better, obtained from the seeing monitor at CTIO. On both nights the atmospheric conditions were photometric.

The individual slit spectra were reduced using standard procedures for long-slit spectroscopy, using IRAF reduction packages. The wavelength calibration was applied to the two-dimensional images by using the tasks FITCOORDS and TRANSFORM after reidentifying the arc spectra in many spatial positions. This procedure helps to remove distortions in the image that may be present because of slit curvature and misalignment with respect to the CCD. The final corrected images show displacements on the order of 1 pixel, which is the precision limit of this method. An additional fine correction for slit misalignment was made using the Hα and Hβ profiles for each exposure. Using IDL the images were redimensioned to 100 times their original size. The normalized Hα and Hβ profiles were then matched and the final result redimensioned to original values. This procedure yields the precise alignment necessary for calculation of diagnostic line intensity ratios. Minor shifts on the order of 1 pixel can introduce considerable errors in line ratios if this method is not applied. The error introduced in line ratios by misalignments can reach 4% on sharp edges of the brightness profile.

For the flux calibrations two standard stars, LTT 7379 and LTT 9239, were observed on both nights. The final sensitivity function obtained from these stars, using the IRAF task

4 Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.

5 For details of the instrument and telescope, see http://www.ctio.noao.edu and click on “Optical Spectrographs,” then on “1.5 m RC spectrograph.”
SENSFUNC, has an rms of 0.02, indicating the good photometric quality of the nights. On the basis of previous similar spectrophotometric observations made with the Isaac Newton Telescope on La Palma, we compute the random error on individual line flux calibrations to be 3%, while the overall possible systematic uncertainty in the stellar flux is about 5%.

2.2. Image Reconstruction

The final emission-line images were obtained from the spatially integrated flux profile in each slit. To obtain the slit profile of integrated fluxes in a given transition, a Gaussian function was fitted to each point along the spatial direction by using IDL routines. The errors adopted for the fits were the standard deviations calculated by the fitting procedure. The profiles for each slit position were then combined and interpolated using a cubic convolution algorithm (Park & Schowengerdt 1983; Rifman & McKinnon 1974) to reconstruct a two-dimensional image of the nebula for that transition. Integration of this final image provides the total observed flux for the nebula, for each line. Note that this procedure gives better estimates of the total flux and relative line intensities than observing just one slit position or aperture, since it takes into account the entire nebula.

Signal-to-noise images were also obtained using the fitted profiles by subtracting the fitted profile from the original section and analyzing the remaining noise. This is a combination of all noise sources in the image (photon statistics, noise introduced by the data reduction procedures, etc.). These errors were then combined with the fitting errors mentioned above, using the usual error propagation expressions to make the final signal-to-noise image. We then quadratically added the 3% random calibration error and the dereddening error computed from the Hα/Hβ reddening map (see § 3.1) to arrive at the overall error for each line flux. This procedure provides precise error estimates for the total fluxes and diagnostic line ratio calculations.

3. OBSERVATIONAL RESULTS

Images were created for all 17 lines detected with sufficient signal-to-noise ratio (S/N). In Figure 3 the images for the most important lines are shown. The important [O iii] 436.3 nm line fell outside our available spectral range and could therefore not be included in our analysis. The images were corrected for reddening as described in the following section. The extracted total line intensities with their fractional total errors are given in Table 1.

Note that all main features are reproduced in these reconstructed line images. The outer ansae show up only in the [N ii] 685.4 nm line and are extremely faint or invisible in all other lines, as they are in the HST original images. The [O iii] 500.7 nm emission comes mainly from the central part of the bright ringlike structure, while Hα comes from farther out, and the outermost part is dominated by [N ii] 685.4 nm. Clearly, we do not reproduce the fine detail visible in the HST image because of our effective spatial resolution of 4" in the observational data. However, the expected ionization stratification for the different ions and the overall nebular structure are clearly seen in our images.

3.1. Reddening Correction and Total Fluxes

The reconstructed images for each line were corrected for reddening by using the Hα/Hβ ratio map shown in Figure 4. The logarithmic correction constant was calculated pixel by pixel using the theoretical value of Hα/Hβ = 2.87 (Osterbrock 1989, p. 422) and the reddening curve of Seaton (1979). We investigated the effect of differential atmospheric refraction on this ratio map. From the air masses of our observed positions and the values given by Filippenko (1982), we computed a correction that we applied to our data. Since we used wide slits (4") and the object is extended, the effect was small but not negligible in the steep gradients near the bright ring structure. The average error due to this effect is about 2% in the high signal-to-noise areas and about 20% in the low signal-to-noise areas. The net effect on the final calculated relative total fluxes is about 0.2% for strong lines and 5% for weak ones, well within the other observed uncertainties.

In Figure 5 we show the [N ii] 658.4 nm image as an example before and after the reddening and differential refraction corrections. The reddening correction was also obtained from the spatially integrated fluxes calculated from the images. The Hα flux was divided by the Hβ flux, and a single value for the logarithmic extinction constant was obtained for the whole nebula. This value was then used to correct the total line intensities. The results for the line intensities were compared with those obtained from the first method and showed no differences to within the calculated uncertainties.

The resulting emission-line fluxes relative to Hβ and their corresponding total errors are shown in Table 1. All total fluxes were obtained by integrating the reddening-corrected (pixel by pixel) images. The value we obtained for the total dereddened Hβ flux was $F_{\text{H}\beta} = 7.2 \times 10^{-13}$ W m$^{-2}$, and the uncorrected flux value was $5.9 \times 10^{-13}$ W m$^{-2}$, corresponding to a value of $E(B-V) = 1.4$ mag.

3.2. Gas Density and Temperature

We calculated the density and temperature maps from the reddening-corrected maps of the [S ii] and [N ii] lines, respectively. The expression relating the sulfur doublet line intensity ratios to the gas density is from de Robertis et al. (1987), which is also used in the IRAF package TEMDEN. The density map is shown in Figure 6. For the temperature map we used the expression given by McCall (1984) as this allowed us to take the density variations over the nebula into account, which we did by using our density map. The difference between using this method and one that assumes constant density is small, since the temperature is only weakly dependent on the density, but systematic.

For the temperature maps, correction for slit misalignment was carried out as done for the Hα/Hβ maps discussed in § 2.1. This correction was not necessary for the density maps since the small wavelength separation of the two lines generates very little deviation. The temperature map obtained after dereddening is shown in Figure 7a. We also show the difference between the temperature map obtained using constant density and our map in Figure 7b. Note that the differences are less than 500 K. The images are clipped for data values with S/N lower than 10 for visual clarity.

3.3. Temperature of the Central Star

With the total fluxes corrected for interstellar reddening, the central star temperature can be calculated. For this, we apply the method described by Harman & Seaton (1966), using the observed fluxes presented in § 3.1 and the central star flux $F_{4793 \text{ Å}} = 1.20 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ obtained from Gathier & Pottasch (1988). It is important to note that this method assumes spherical symmetry and a blackbody SED for the

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6 See http://heritage.stsci.edu/2002/25/original.html.
ionizing star. This is not necessarily true as has been shown by many authors (for recent work see Rauch et al. 2000). Here we use a blackbody spectrum modified by the major H and He absorption edges, and below we show by comparison with stellar evolution models from Blöcker (1995) that this is a reasonable method.

From the H/β and He λ 468.6 nm line fluxes we obtain, respectively, $T_Z(\text{H}) = 70,000$ K and $T_Z(\text{He} \, \lambda 468.6) = 106,000$ K. The value obtained for $T_Z(\text{H})$ with our fluxes differs slightly from the one obtained by Gathier & Pottasch (1989) but is within the expected (large) uncertainties of the method. These values are more reliable than previously calculated ones since we have precise integrated fluxes for the whole nebula.

The Zanstra temperatures for H and He λ 468.6 are not necessarily equal and do not correspond to the effective temperature of the central star if the nebula is not optically thick in all directions (Gruenwald & Viegas 2000). NGC 6369 is optically thin for radiation shortward of 91.2 nm (Lyman continuum) since a rough estimate of the total luminosity in the optical lines is ≈14% of that shortward of 91.2 nm. Most of the UV escapes the nebula, and therefore we expect the $T(\text{H})$ to be lower than the $T(\text{He})$, as indeed found above.

4. PHOTOIONIZATION MODELS

The photoionization code applied here was described in detail by Gruenwald et al. (1997). It uses a cube divided into cells, each having a given density. This allows arbitrary density distributions to be studied. The input parameters are the ionization source characteristics (luminosity, spectrum, and temperature), element abundances, density distribution, and...
the distance to the object. The conditions are assumed uniform within each cell where the code calculates the temperature and ionic fractions. These values are used to obtain emission-line emissivities for each cell.

The final data cube can be oriented to reproduce the observed morphology. The orientation of the structure is thus also determined. The line intensities and other relevant quantities are then obtained after projection onto the plane of the sky. Note that because we lack velocity information, we cannot specify whether an ansa is in front of or behind the main nebula.

The structure adopted for NGC 6369 is shown in Figure 8 as it is oriented relative to the observer. The choice of the structure was based on the density map obtained from the observations. As shown in Monteiro et al. (2000), closed shells were not able to reproduce the decrease in the density profile in the central regions of NGC 3132. For the same reason, we adopt an hourglass shape for the main structure of NGC 6369, as its density map shows the same decrease in the central regions. We include random fluctuations in the density grid to simulate the clumpiness observed in images, as well as a density gradient along the main axis of the bipolar structure. The fluctuations were set to vary between the maximum and the minimum densities measured from the observational data. The rotation angles relative to the \( x \), \( y \), and \( z \)-axis are 70°, 10°, and 0°, respectively, with the symmetry axis of the main structure being the \( x \)-axis. The model resolution of 100\(^3\) cells was limited by computer memory.

The ionizing spectrum adopted for the central source is a modified blackbody with a break at 54.4 eV. This was necessary to fit both the [O\(\text{iii}\)] and He\(\text{ii}\) line intensities, of which the last one is particularly sensitive to the depth of the break. This break is also present in the more precise theoretical atmospheric models presented by Rauch et al. (2000). The cutoff at 54.4 eV is one of the most prominent features that differentiates this spectrum from that of a blackbody, followed by the 13.6 eV hydrogen cutoff and absorption lines. The effective temperature and luminosity of this modified blackbody are listed in Table 2.

4.1. Model Results

We present here the main results obtained with the photoionization model. The total line intensities are given in Table 2,
as well as the fitted abundances and ionizing star characteristics. Projected line images for the most important transitions are shown in Figure 9.

The model image size is fitted to the observed size for the $[\text{N} \text{II}]$ 658.4 nm line, as well as constrained by the absolute H/\(\beta\) flux. The distance of 1550 pc that we determine is also constrained by fitting all the line fluxes and the shape of the nebula simultaneously, and for this reason it is fundamentally different from classical distance determination methods, as it needs no assumptions to be made. One cannot increase the distance and simply make the nebula larger to fit the optical image, as the line ratios would change significantly. Three-dimensional ionization models such as this one cannot simply be scaled, thus placing much more stringent constraints on all derived parameters, including the distance. Note that this model distance is within 1 adjusted standard deviation of the average of all the observationally determined distances given in § 1. Figure 10 shows the observed $[\text{N} \text{II}]$ image with the corresponding model image contours overlaid for the obtained distance. The $[\text{S} \text{II}]$ ratio map obtained with the model is shown in Figure 11.

5. DISCUSSION AND CONCLUSIONS

We have presented spectrophotometric maps of NGC 6369. These maps provided spatially resolved information for many emission lines and precise total fluxes for the whole nebula. The images produced with this technique were used to study the nebula with the usual diagnostic ratios. Each image was corrected for reddening pixel by pixel using the H/\(\alpha\)/H/\(\beta\) image. This correction led to some significant differences between the corrected and uncorrected images, as was shown in Figures 5 and 7.

The H/\(\alpha\)/H/\(\beta\) map shows some interesting features. In Figure 4 we show that the extinction is not uniform across the nebula, as it varies between 6 and 18. The structure follows the main nebular morphology, which could indicate that dust and neutral material are present. This is to be expected since the nebula shows a very clumpy structure, which may cause shadowing within the gas, allowing for the survival of grains and neutral material. The prominent features on either side of the nebula do not show significant differences between the corrected and uncorrected images, as was shown in Figures 3 and 5.

The temperature map derived from the observed integrated line-of-sight intensities showed some structure, but because of the low S/N this should be treated with caution. Within the errors and resolution of our observations the temperature can be considered to be constant across the nebula.

We also show that the density map indicates a decrease in density for the central regions. This decrease, as has been discussed by Monteiro et al. (2000), is not compatible with a closed shell structure. On the basis of this map we propose an hourglass structure for the main nebula, which has reproduced all the observational features of NGC 6369. This indicates that
one needs to use the \([\text{S} \equiv]\) ratio in addition to the images to
distinguish between open and closed structures.

The position of the outer condensations or ansæ, which are
offset by \(30^\circ/C_{14}\) from the main nebular symmetry axis, was ob-
tained by matching model images with the observed line
images (Fig. 3), as well as matching the model \([\text{S} \equiv]\) density
map with the observed map (Fig. 6). The presence of these
condensations can be accounted for by earlier ejection of mat-
ter, and precession can account for their deviation from the
symmetry axis. Many authors have dealt with these issues; for
more nearly complete discussions and models, see, for ex-
ample, Cliffe et al. (1996, 1995), García-Segura (1997), and
Livio & Pringle (1997).

Some of the parameters we have derived (and use as a
sanity check) are the following:

1. The total luminosity of the observed lines, \(L_I = 1150 L_{\odot}\),
and that derived from the SED by integrating the \(F_3\) curve,
\(L_o = 7.1 \times 10^{-4} d^2\), where \(d\) is the distance to NGC 6369 in
parsecs, resulting in \(L_o = 1700 L_{\odot}\). Correcting this value by
using the method of Myers et al. (1987), we obtain 2550 \(L_{\odot}\).

The luminosity of the central star is \(L_{\text{tot}} = 8100 L_{\odot}\), so the
ratios of the line and optical+IR luminosities to the total lu-
minosity are, respectively, \(L_I/L_{\text{tot}} = 0.14\) and \(L_o/L_{\text{tot}} = 0.3\).

| TABLE 2 | OBSERVED AND MODEL LINE FLUXES AND MODEL CENTRAL STAR PROPERTIES |
|----------|----------------------------------|
| Parameter | Observed | Model |
| \(T_e\) (kK) | 70–106 | 91 |
| \(L_x/L_y\) | ...... | 8100 |
| Density | 1000–5400 | 300–5400 |
| He/H | \(1.14 \times 10^{-1}\) | 3.3 \(\times 10^{-4}\) |
| C/H | \(1.0 \times 10^{-4}\) | 6.1 \(\times 10^{-4}\) |
| N/H | \(6.5 \times 10^{-5}\) | 7.5 \(\times 10^{-6}\) |
| S/H | \(7.5 \times 10^{-6}\) | \[\text{Ne} \equiv\] 386.8 nm | 0.9 | 0.9 |
| \[\text{N} \equiv\] 658.4 nm | 0.73 | 0.78 |
| \[\text{O} \equiv\] 500.7 nm | 12.41 | 12.33 |
| \[\text{He} \equiv\] 468.6 nm | 0.014 | 0.013 |
| \[\text{He} \equiv\] 587.6 nm | 0.163 | 0.169 |
| \[\text{O} \equiv\] 630.0 nm | 0.052 | 0.048 |
| \[\text{S} \equiv\] 671.7 nm | 0.044 | 0.047 |
| \[\text{S} \equiv\] 673.1 nm | 0.066 | 0.063 |

\(a\) Value obtained from Peña et al. (2001).

![3-D structure of NGC 6369](image-url)
Fig. 9.—Projected line images obtained with the photoionization model. North is up, and east is to the left.

Fig. 10.—Contours of the model [N ii] image over the observed image for \( d = 1550 \) pc. North is up, and east is to the left.

Fig. 11.—[S ii] line ratio obtained with the model. North is up, and east is to the left.
Assuming that the absorbed flux is reradiated in the IR, mainly the IRAS bands, the integrated optical+IR luminosity indicates that about 70% of the UV flux (Lyman continuum) escapes from the nebula. This is not implausible as the nebula is open at its “poles” and is clumpy, allowing the radiation to pass through the many “holes.”

2. From the input matter distribution and abundances used in the model, we calculate the mass of the nebular ionized gas to be $M_{\text{n neb}} = 1.8 M_\odot$. If we now use our values of luminosity and temperature for the central star and compare them with the evolutionary models of Blöcker (1995), we can obtain the mass of the central core. Using this procedure, we can see from Figure 12 that the best-fitting track for our data corresponds to a mass somewhat higher than $M_{\text{core}} = 0.625 M_\odot$, say, $=0.65 M_\odot$, and to an initial mass of $M_0 = 3 M_\odot$. If we sum our nebular and core masses, we obtain $M_{\text{core}} + M_{\text{n neb}} = 2.4 M_\odot$ approximately. If we use the line intensity errors as a measure of the goodness of the model results and combine the luminosity and temperature errors, we obtain approximately 20%–25% for the uncertainty in $M_{\text{core}} + M_{\text{n neb}}$, placing the obtained initial stellar mass within the uncertainty of our determination. The value for $M_{\text{n neb}}$ calculated from the model input density is a lower limit estimate of the total nebular mass as at least some material is present in the form of dust, as indicated qualitatively by our extinction map structure. In addition, there may be neutral gas for which we have no constraints.

Note that typical parameters for a WC4 PN central star from Allen (1964, p. 216) are $T = 90 \, \text{kK}$ and $R = 0.4 \, \text{R}_\odot$, very close to our derived values of 91,000 K and 0.4 $\text{R}_\odot$. Using $g = G M/R^2$ in cgs units, we obtain $\log g = 5.1$, which is much lower than the value of 5.8 derived from the depth of our He break. This is because the central star has an extended atmosphere, again showing the consistency of the model results.

Using our photoionization code and the proposed structure, we obtained a complete three-dimensional model for NGC 6369. The fitted model line intensities show excellent agreement with the observed values. The obtained distance $d = 1550 \, \text{pc}$ is well within the range present in the literature obtained from different methods. The model temperature for the ionizing star is similar to the Zanstra (He) value discussed in §3.3. The temperature and luminosity values obtained from the model, as well as the total nebular plus central star mass, show good agreement with the stellar evolution models of Blöcker (1995).

Using multiple long-slit spectroscopy, we can determine accurate distances, three-dimensional structures, abundances, ionized masses, central star masses, luminosities, and temperatures to any spatially resolved emission-line nebula, assuming there are no strong shocks or extreme morphologies involved.

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