OBSERVATIONAL STUDY OF THE MULTISTRUCTURED PLANETARY NEBULA NGC 7354

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ABSTRACT

We present an observational study of the planetary nebula (PN) NGC 7354 consisting of narrowband Hα and [N ii]λ6584 imaging as well as low- and high-dispersion long-slit spectroscopy, and VLA-D radio continuum. According to our imaging and spectroscopic data, NGC 7354 has four main structures: a quite round outer shell and an elliptical inner shell, a collection of low-excitation bright knots roughly concentrated on the equatorial region of the nebula, and two asymmetrical jet-like features, not aligned either with the shells’ axes, or with each other. We have obtained physical parameters like electron temperature and electron density as well as ionic and elemental abundances for these different structures. Electron temperature and electron density slightly vary throughout the nebula going from $\simeq$11,000 to $\simeq$14,000 K, and from $\simeq$1000 to $\simeq$3000 cm$^{-3}$, respectively. The local extinction coefficient $E(B-V)$ shows an increasing gradient from south to north and a decreasing gradient from east to west consistent with the number of equatorial bright knots present in each direction. Abundance values show slight internal variations but most of them are within the estimated uncertainties. In general, abundance values are in good agreement with the ones expected for PNe. Radio continuum data are consistent with optically thin thermal emission. Mean physical parameters derived from the radio emission are electron density $n_e = 710$ cm$^{-3}$ and $M(H\alpha) = 0.22 M_\odot$. We have used the interactive three-dimensional modeling tool SHAPE to reproduce the observed morphokinematic structures in NGC 7354 with different geometrical components. Our observations and model show evidence that the outer shell is moving faster ($\simeq$35 km s$^{-1}$) than the inner one ($\simeq$30 km s$^{-1}$). Our SHAPE model includes several small spheres placed on the outer shell wall to reproduce equatorial bright knots. Observed and modeled velocity for these spheres lies between the inner and outer shells velocity values. The two jet-like features were modeled as two thin cylinders moving at a radial velocity of $\simeq$60 km s$^{-1}$. In general, our SHAPE model is in very good agreement with our imaging and spectroscopic observations. Finally, after modeling NGC 7354 with SHAPE, we suggest a possible scenario for the formation of the nebula.

Key words: ISM: abundances – ISM: kinematics and dynamics – planetary nebulae: individual (NGC 7354)

1. INTRODUCTION

Since the recognition that winds from the central stars of planetary nebulae (PNe) play an important role in the shaping of these objects (e.g., Kwock et al. 1978; Balick 1987), and that only a small fraction of them show circular symmetry, the interest in PN morphology has triggered an active field in both theoretical and observational astronomy. Many studies have been devoted to classifying (e.g., Balick 1987; Schwarz et al. 1992; Manchado et al. 1996) and modeling the basic morphologies observed (circular, elliptical, and bipolar) with noticeable success (e.g., Balick et al. 1987; Hajian et al. 1997). However, high-resolution images have shown that the morphologies of PNe are far from simple. Multiple shells, multipolar structures, highly collimated outflows, microstructures, and peculiar geometries are present in many PNe, and cannot be explained with simplistic models (e.g., Sahai & Trauger 1998; Miranda et al. 2006, 2009). Nowadays, other physical processes are probably present, so that most likely the shaping of PNe is a result of many processes acting at the same time (e.g., Balick & Frank 2002). In order to understand complex PNe, the first step is to identify the structural components present and to define their nature. High-resolution, spatially resolved spectroscopy combined with narrowband imaging has proved to be a powerful tool to disentangle the structural components in PNe, to infer their nature, and to constrain the ejection processes involved in their formation (Miranda & Solf 1992; Vázquez et al. 1998, 1999, 2008; Guerrero et al. 2008; López et al. 2000).

At first glance NGC 7354 looks like an elliptical PN, extensive Hα, [O iii]λ5007, [N ii]λ6584, and mid-infrared imaging and spectroscopic data have revealed that it possesses a more complex structure (Sabbadin et al. 1983; Balick 1987; Hajian et al. 1997; Phillips et al. 2009). In particular, Balick (1987) described this nebula as consisting of an inner halo, a thin bright rim, two spike-like tails, and low-excitation patches projected onto the rim–halo interface. The large-scale structures observed in NGC 7354 are qualitatively well described using the interacting winds theory (e.g., Balick et al. 1987; Mellemá 1995; Hajian et al. 2007), but no deep analysis has been carried out for the small-scale structures and their relationship with the large-scale ones.

In this work, we present a detailed observational study of the morphology, internal kinematics, and physical and chemical properties of NGC 7354. These data allow us to discuss and model each of the components present in the object and to suggest a possible scenario for the formation of this nebula.

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2. OBSERVATIONS AND RESULTS

2.1. Optical Imaging

Narrowband images of NGC 7354 were obtained on 1997 July 24 with the Nordic Optical Telescope (NOT) and the HiRAC camera equipped with a Loral CDD of 2048 × 2048 pixels and a plate scale of 0.′′11 pixel. Two narrowband filters were used: [N II]λ6584 (Δλ = 10 Å) and Hα (Δλ = 10 Å). The exposure time for both filters was 900 s. Seeing was about 0.′′9 during the observations.

Figure 1 shows a mosaic of our Hα and [N II] images, including unsharp masking images in both filters constructed to show both the large- and small-scale structures in the nebula. In these images, we can identify the main structures previously described by other authors: the outer shell, the elliptical inner shell, the bright equatorial knots, and the two jet-like features. In the following, we will describe in more detail each of these structures as well as new morphological details that have not been previously mentioned.

The outer shell looks like a round envelope in the high-contrast images but it appears as a faint cylindrical structure in the low-contrast images. Its size is ≃33″ × 29″ with the major axis oriented at the position angle (P.A.) ≃ 15°. The outer shell is brighter in Hα than in [N II] although in [N II] several bright knots are observed at the edges of it.

The inner shell presents an elliptical shape with its major axis oriented at P.A. ≃ 30° and a major and minor axes length of ≃21″ × 16″, respectively. This structure is noticeably fainter in [N II] than in Hα. Moreover, the regions along the minor axis are particularly bright in Hα. A closer inspection of the images shows that the polar regions deviate from the elliptical shape and appear as two bubbles. This is particularly noticeable in Hα. We will refer to these regions of the inner shell as the polar caps.

The bright equatorial knots are observed in [N II] but not in Hα. They are mainly concentrated in two groups, east and west, and along the equatorial plane of the outer and inner shells.

The two jet-like features are bright in [N II] but much fainter in Hα. The northern feature is oriented at P.A. ≃ 13° and extends ≃7″. The southern feature is oriented at P.A. ≃ 205°, extends ≃11″, and appears narrower than the northern one. We note that the orientation of these two features does not coincide with each other nor with the orientation of the outer and inner shells.

In order to improve the view of NGC 7354, we retrieved a Hubble Space Telescope (HST) image from the MAST Archive (Proposal ID: 7501; PI: A. Hajian; date of observation: 1998 July 21; filter F658N; exposure time 1000 s). Figure 2 shows this image. The morphology of the outer and inner shells is similar to that observed in ground-based images (Figure 1). The jet-like features appear as cometary tails with a bright knot facing

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7 The NOT is jointly operated on the island of La Palma by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

8 Some of the data presented in this paper were obtained from the Multimission Archive at the Space Telescope Science Institute (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NAG5-7584 and by other grants and contracts.
3.6 cm radio continuum. Contour levels are 8, 18, 35, 60, 100, 150, 200, 270, and 400 times $144 \mu$Jy beam$^{-1}$, the rms noise in the map. The half-power beam width ($8.0' \times 6.5', \text{P.A.} -86'$) is shown in the upper right corner.

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Figure 3. Gray-scale and contour uniform-weighted map of NGC 7354 at the 3.6 cm radio continuum. Contour levels are 8, 18, 35, 60, 100, 150, 200, 270, and 400 times $144 \mu$Jy beam$^{-1}$, the rms noise in the map. The half-power beam width ($8.0' \times 6.5', \text{P.A.} -86'$) is shown in the upper right corner.

Figure 4. The central star and faint tails directed outward. They present a knotty structure, particularly the southern one. The HST image resolves the bright equatorial knots into a series of small knots and filaments embedded in diffuse emission.

2.2. Radio Continuum

The $\lambda 3.6$ cm radio continuum observations were made with the Very Large Array (VLA) of the NRAO$^9$ on 1996 May 31 in the DnC configuration. The standard VLA continuum mode with a bandwidth of 100 MHz and two circular polarizations was employed. Phase center was set at R.A.(2000.0) = 22$^h$40$^m$20$^s$.1, decl.(2000.0) = +61$^\circ$17'06".0. The flux calibrator was 3C48 (adopted flux density $3.3 \text{ Jy}$), and the phase calibrator was 0019+734 (observed flux density 1.0 Jy). Total on-source integration time was 30 minutes. The data were calibrated and processed using standard procedures of the Astronomical Image Processing System (AIPS) package of the NRAO.

Figure 3 shows a uniform-weighted map of NGC 7354. The emission presents a circular morphology and extends $\simeq 42''$ in diameter. Two emission maxima are observed separated by $\simeq 10''$ and oriented at P.A.$\simeq 100^\circ$. These emission maxima coincide with the Hα bright regions observed along the minor axis of the inner shell.

From our data we derive a peak flux density of 72 mJy beam$^{-1}$ at position R.A.(2000.0) = 22$^h$40$^m$20$^s$.44, decl.(2000.0) = +61$^\circ$17'06".8, and a total flux density of 502 $\pm$ 4 mJy. We note that our map is similar to that obtained by Terzian et al. (1974), with the flux density values obtained in both works consistent with each other and with optically thin thermal emission. Adopting a distance of 1.5 kpc for the nebula (Sabbadin 1986, see Section 3.1) and following the formulation by Mezger 

2.3. Low-resolution Spectroscopy

Low-resolution, long-slit spectra were obtained with the Boller & Chivens spectrograph mounted on the 2.1 m telescope at the San Pedro Mártir Observatory (OAN-SPM)$^{10}$ during three observing runs: 2002 June 14, 2002 August 7, and 2002 December 10 and 11. A CCD SITe with $1024 \times 1024$ pixels was used as a detector. We have used a 400 lines mm$^{-1}$ dispersion grating and a slit width of $2''$ giving a spectral resolution (FWHM) of 7 Å. Spectra reduction was performed using IRAF$^{11}$ standard procedures. We have used four slit positions to cover specific regions of the nebula. Figure 4 shows these slits, labeled A to D, and the regions extracted from each long-slit spectrum overlapped on the unsharp masking [N II] image. Regions are denoted by a letter referring to the slit position followed by a sequence number along the slit. In total, 21 regions in NGC 7354 have been analyzed.

Table 1 presents the dereddened line fluxes, observed H$\beta$ flux, and the logarithmic extinction coefficient $C_{H\beta}$ for each region; the last has been derived from the observed H$\alpha$/H$\beta$ ratio assuming case B recombination. The fluxes have been dereddened applying the extinction law by Cardelli et al. (1989). Electron temperature ($T_e$) has been derived from the [O III] and/or [N II] emission lines, while electron density ($N_e$) has been derived from the [S ii], [Cl iii], and/or [Ar iv] emission lines, in both cases using the Five-Level Atom Diagnostic Package NEBULAR (DeRobertis et al. 1987; Shaw 

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$^9$ The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities Inc., under cooperative agreement with the National Science Foundation.

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$^{11}$ The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Table 1
Dereddened Emission-line Fluxes (Normalized to Hβ = 100)

| Ion   | λ      | f_μ | B7  | C1  | C2  | C3  | C4  | C5  | C6  | D1  | D2  | D3  |
|-------|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Hγ    | 4340   | 0.177| 60.3|     |     |     |     |     |     |     |     |     |
| [O iii] | 4365 | 0.149| 13.5| 14.1| 18.3| 15.4| 15.4| 18.7| 25.1| 27.3| 18.8| 17.3| 18.2|
| Hε    | 4471   | 0.115| 6.3  | 6.6  | 6.6  | 6.6  | 6.6  | 6.6  | 6.6  | 6.6  | 6.6  | 6.6  | 6.6  |
| He ii | 4686   | 0.050| 3.8  | 56.3 | 51.6 | 76.9 | 24.8 | 8.4  | 46.9 | 56.9 | 68.1 | 74.9 | 55.5 |
| [Ar iv] | 4711 | 0.042| 8.7  | 7.5  | 11.5 | 7.7  | 7.7  | 8.3  | 9.4  | 9.4  | 10.3 | 7.6  |     |
| [Ar iv] | 4740 | 0.034| 9.3  | 7.1  | 10.9 | 6.6  | 6.6  | 6.3  | 5.9  | 7.3  | 7.2  | 6.8  |     |
| Hβ    | 4861   | 0.000| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0|     |
| [O iii] | 4959 | −0.026| 476.1| 411.5| 408.1| 404.8| 457.8| 454.3| 493.0| 450.3| 395.1| 381.2| 452.4|
| [N ii] | 5007 | −0.038| 1394.9| 1216.2| 1202.8| 1198.9| 1358.4| 1353.1| 1452.8| 1323.4| 1169.0| 1125.3| 1333.3|
| [N ii] | 5755 | −0.185| 0.5  | 0.9  | 0.3  | 0.8  | 0.8  | 0.6  | 0.6  | 0.6  | 0.6  | 0.6  | 1.1  |
| Hε    | 5876   | −0.203| 15.4 | 9.8  | 10.9 | 8.2  | 13.7 | 16.3 | 11.4 | 9.7  | 9.0  | 8.5  | 10.7 |
| [O i]  | 6300   | −0.263| 5.2  | 0.6  | 0.2  | 1.0  | 0.0  | 0.4  | 0.4  | 0.2  | 0.2  | 0.2  | 0.9  |
| [S ii] | 6312   | −0.264| 1.8  | 2.3  | 1.6  | 1.5  | 2.8  | 2.3  | 2.2  | 1.7  | 2.1  | 2.1  |     |
| [O i]  | 6364   | −0.271| ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 0.4  |
| [N ii] | 6458   | −0.296| 27.2 | 5.0  | 14.7 | 5.7  | 8.5  | 6.9  | 4.5  | 4.5  | 4.4  | 3.9  | 13.3 |
| Hα    | 6565   | −0.298| 285.0| 278.4| 283.4| 281.8| 279.3| 281.5| 280.2| 276.5| 280.7| 280.9| 281.8|
| [N ii] | 6584   | −0.300| 65.7 | 13.9 | 41.4 | 11.7 | 23.8 | 21.8 | 13.2 | 13.0 | 12.2 | 11.3 | 42.3 |
| Hε    | 6678   | −0.313| 5.3  | 2.9  | 3.0  | 2.6  | 4.4  | 4.0  | 3.9  | 3.0  | 2.8  | 2.6  | 3.2  |
| [S ii] | 6717   | −0.318| 4.6  | 1.3  | 2.7  | 1.0  | 1.8  | 2.7  | 1.2  | 1.2  | 1.1  | 1.1  | 2.3  |
| [S ii] | 6731   | −0.320| 5.5  | 1.7  | 3.9  | 1.4  | 2.1  | 2.8  | 1.6  | 1.6  | 1.6  | 1.5  | 3.4  |
| Hε    | 7065   | −0.364| 4.0  | 2.7  | 3.2  | 2.3  | 3.5  | 4.1  | 3.2  | 2.7  | 2.6  | 2.2  | 2.6  |
| [Ar iii] | 7135 | −0.374| 14.1 | 15.1 | 17.0 | 15.3 | 16.4 | 17.2 | 16.7 | 15.5 | 15.0 | 14.0 | 15.6 |
| [Ar iv] | 7236 | −0.387| 1.2  | 1.2  | 1.0  | 1.0  | 0.9  | 1.2  | 1.5  | 1.2  | 1.1  | 1.1  |     |
| Hε    | 7281   | −0.393| 0.4  | 0.5  | 0.4  | 0.8  | 0.6  | 0.6  | 0.6  | 0.6  | 0.6  | 0.6  | 0.6  |
| [O iii] | 7320  | −0.398| 1.6  | 1.0  | 1.5  | 1.0  | 1.4  | 1.6  | 0.9  | 1.2  | 1.2  | 1.0  | 1.4  |
| [O iii] | 7330  | −0.400| 0.6  | 0.8  | 1.2  | 0.9  | 0.8  | 0.8  | 0.8  | 0.8  | 0.8  | 0.8  | 0.8  |
| c(Hβ) |        | 2.44 | 2.04 | 1.96 | 1.86 | 1.73 | 2.05 | 2.12 | 2.12 | 1.98 | 1.99 | 2.03 |     |
| log 10(Hβ) |  | −16.873| −14.998| −14.898| −15.040| −15.016| −15.901| −15.891| −15.461| −15.235| −15.311| −15.417|     |

Extinction within the nebula, as indicated by c(Hβ), shows a slight increase from south to north with values ranging from \(\sim 1.7\) to \(\sim 2.4\), respectively. Relatively high values of c(Hβ) \(\sim 2.4\) are found in the low-excitation equatorial knots. These values can be compared to those in the surroundings of the knots where

the readout and photon noise, and they are propagated along the calculation of physical quantities. Whenever possible, \(N_e\) values were calculated using the value of \(\lambda r\) derived from the corresponding high- or low-excitation ion, [O iii] or [N ii], respectively.
the extinction decreases up to $\alpha_{HI} \approx 1.7$. This result suggests that the equatorial knots are denser and/or contain more dust than the rest of the nebula.

Electron density slightly increases inward from the outer shell (regions B1 and C6) with values of $\approx 1000$ cm$^{-3}$ to the inner regions of the inner shell (region B4) where values of $\approx 2400$ cm$^{-3}$ are found. The bright equatorial knots are clearly denser than both the outer and inner shells with an average density of $\approx 2600$ cm$^{-3}$. For the jet-like features, the electron density is relatively low with values around $\approx 1300$ cm$^{-3}$.

Electron temperature also seems to slightly increase from $\approx 13,000$ K at the walls of the outer shell (regions B1, B6, and B7) to $\approx 15,000$ K at the center of the inner shell (region B3). In the bright equatorial knots, electron temperature ranges from $\approx 10,000$ to $\approx 12,400$ K. For the northern jet-like feature, no [O III] and [N II] lines were detected with a good signal-to-
Kingsburgh & Barlow (1994), respectively. Table 4 also lists IONIC in IRAF and using the ionization correction factors by and 4, respectively. They have been obtained with the task abundance variations, within the estimated uncertainties, are \( \sim \) electron temperature of noise ratio; in the southern jet-like feature, we have obtained an

Table 4

| Region | He/H | O/H | N/H | S/H | Ar/H |
|--------|------|-----|-----|-----|------|
| A1     | 0.120 ± 0.010 | 8.72 ± 0.05 | 8.39 ± 0.35 | 6.67 ± 1.54 | 6.38 ± 0.10 |
| A2     | 0.118 ± 0.001 | 8.19 ± 0.14 | 7.94 ± 0.28 | 6.41 ± 0.14 | 6.05 ± 0.01 |
| A3     | 0.116 ± 0.001 | 8.58 ± 0.15 | 8.31 ± 0.21 | 6.88 ± 0.09 | 6.35 ± 0.01 |
| A4     | 0.121 ± 0.001 | 8.50 ± 0.40 | 7.94 ± 0.60 | 6.63 ± 0.27 | 6.30 ± 0.01 |
| A5     | 0.119 ± 0.001 | 8.21 ± 0.28 | 8.02 ± 0.59 | 6.36 ± 0.28 | 6.09 ± 0.14 |
| B1     | 0.118 ± 0.002 | 8.73 ± 0.11 | 7.76 ± 0.13 | 7.06 ± 0.05 | 6.47 ± 0.10 |
| B2     | 0.120 ± 0.002 | 8.84 ± 0.08 | 8.05 ± 0.12 | 7.14 ± 0.04 | 6.46 ± 0.10 |
| B3     | 0.110 ± 0.001 | 8.15 ± 0.18 | 7.90 ± 0.26 | 6.40 ± 0.14 | 5.95 ± 0.01 |
| B4     | 0.124 ± 0.001 | 8.81 ± 0.04 | 7.94 ± 0.07 | 6.97 ± 0.03 | 6.51 ± 0.01 |
| B5     | 0.122 ± 0.001 | 8.82 ± 0.05 | 7.94 ± 0.07 | 7.07 ± 0.03 | 6.51 ± 0.01 |
| B6     | 0.119 ± 0.001 | 8.48 ± 0.15 | 8.38 ± 0.21 | 6.72 ± 0.10 | 6.21 ± 0.01 |
| B7     | 0.117 ± 0.002 | 8.72 ± 0.16 | 8.13 ± 0.18 | 7.03 ± 0.07 | 6.44 ± 0.10 |
| C1     | 0.111 ± 0.006 | 8.54 ± 0.89 | 8.39 ± 4.87 | 6.82 ± 1.90 | 6.46 ± 0.40 |
| C2     | 0.111 ± 0.003 | 8.60 ± 0.30 | 8.36 ± 0.45 | 6.81 ± 0.20 | 6.45 ± 0.03 |
| C3     | 0.120 ± 0.006 | 8.61 ± 0.27 | 8.31 ± 0.74 | 6.83 ± 0.36 | 6.49 ± 0.04 |
| C4     | 0.127 ± 0.002 | 8.65 ± 0.26 | 8.37 ± 0.33 | 6.86 ± 0.14 | 6.41 ± 0.02 |
| C5     | 0.120 ± 0.003 | 8.45 ± 0.55 | 8.23 ± 0.72 | 6.71 ± 0.29 | 6.27 ± 0.02 |
| C6     | 0.120 ± 0.005 | 8.76 ± 0.23 | 8.25 ± 0.97 | 7.07 ± 0.33 | 6.40 ± 0.10 |
| D1     | 0.122 ± 0.007 | 8.75 ± 0.14 | 8.06 ± 0.16 | 6.77 ± 0.08 | 6.51 ± 0.10 |
| D2     | 0.118 ± 0.002 | 8.70 ± 0.01 | 7.94 ± 0.13 | 7.03 ± 0.06 | 6.44 ± 0.10 |
| D3     | 0.120 ± 0.002 | 8.72 ± 0.13 | 8.53 ± 0.17 | 7.01 ± 0.09 | 6.43 ± 0.10 |
| PNeb\(^a\) | 0.12 ± 0.02 | 8.68 ± 0.15 | 8.35 ± 0.25 | 6.92 ± 0.30 | 6.39 ± 0.30 |
| TIPNe\(^b\) | 0.13 ± 0.04 | 8.65 ± 0.15 | 8.72 ± 0.15 | 6.91 ± 0.30 | 6.42 ± 0.30 |
| H\(^c\) | 0.10 ± 0.01 | 8.70 ± 0.04 | 7.57 ± 0.04 | 7.06 ± 0.06 | 6.42 ± 0.04 |
| Sun\(^d\) | 0.09 ± 0.01 | 8.66 ± 0.05 | 7.78 ± 0.06 | 7.14 ± 0.05 | 6.18 ± 0.08 |

Note. Except for He, all abundances relative to H are logarithmic values with log H = +12. Final rows are for comparison.

\(^a\) Average for PN (Kingsburgh & Barlow 1994).

\(^b\) Average for Type I PNe (Kingsburgh & Barlow 1994).

\(^c\) Average for H II regions (Shaver et al. 1983).

\(^d\) The Sun (Grevesse et al. 2007).

In regions A5, B1, and D3, He abundances shown are an upper limit.

Noise ratio; in the southern jet-like feature, we have obtained an electron temperature of \( \sim 12,000 \) K (regions A5 and D3).

Ionic and elemental abundances values are listed in Tables 3 and 4, respectively. They have been obtained with the task IONIC in IRAF and using the ionization correction factors by Kingsburgh & Barlow (1994), respectively. Table 4 also lists abundances in other objects for comparison purposes. Small abundance variations, within the estimated uncertainties, are observed throughout NGC 7354. In general, we found that all our abundance determinations are consistent with those of PN; see Table 4. Since neither He nor N overabundance is observed, as in the case of Type I PNe, we can say that it behaves like a Type II PN.

Elemental abundances for NGC 7354 have been reported by several authors (Hajian et al. 1997; Martins & Viegas 2002; Perinotto et al. 2004a; Stanghellini et al. 2006). However, a comparison of our abundance estimates with those from the literature is not straightforward since we have obtained abundance values for several slit positions and specific regions along them. In the case of Hajian et al. (1997), they report abundance values of six regions along a slit position very similar to our slit A. Their abundances tend to be two or three times higher than ours in cases of O/H, N/H, and S/H but lower in He/H and similar in Ar/H. Comparison with other studies can only be done through average values along each of our slit positions or the total average obtained from all our studied regions. We have compared our total averaged O/H, N/H, S/H, Ar/H abundances with those from Perinotto et al. (2004a) and Stanghellini et al. (2006). In both studies, their abundances seem to be lower than ours, but in the case of Stanghellini et al. (2006) this difference may be due to the fact that they consider the PN as a whole and excluded special features in the nebula.

2.4. High-resolution Spectroscopy

High-resolution, long-slit spectra were obtained in 2002 July 15–17 and 2007 July 10–17 with the Manchester Echelle Spectrometer (MES; Meaburn et al. 2003) mounted on the 2.1 m telescope at San Pedro Mártir Observatory (OAN-SPM). A Site CCD with 1024 \( \times \) 1024 pixels was used as a detector. Binning of 1 \( \times \) 1 and 2 \( \times \) 2 were used in 2002 and 2007, respectively. Slit width was 1.6\(^\prime\) and the achieved spectral resolution (FWHM) is 12 km\(^s^{-1}\). The slit was oriented north–south and centered at several right ascensions (R.A.s) across the nebula, except in those slits that covered the jet-like features, which have been centered on the central star and oriented at P.A.s 13\(^\circ\) and 25\(^\circ\). Figure 5 shows the used slit positions, numbered from 1 to 8, superimposed on the unsharp masking [N II] image. Data reduction was carried out with the IRAF package.

Gray-scale, position–velocity (PV) maps, derived from the eight long-slit spectra, are shown in Figure 6 for the H\(\alpha\), [N II]\(\lambda\)6584, and He\(\alpha\)\(\lambda\)6660 emission lines. From the long-slit spectra, we derived a heliocentric systemic velocity of \(-42 \pm 2\) km\(^s^{-1}\) for NGC 7354, in excellent agreement with \(-41 \pm 2\) km\(^s^{-1}\) deduced by Sabbadin et al. (1983).
paper, we will consider the systemic velocity as the origin for quoting internal radial velocities and the declination (decl.) of the central star as the origin for quoting distance measurements. The PV maps allow us to recognize the structural components that have been identified in the direct images. In the following, we will describe the spatio-kinematical properties of these components.

The \([\text{N}\,\text{II}]\) emission from the outer shell is recognizable at slit positions 1, 2, 3, 5, and 6. The emission is very faint, and in the central nebular regions it appears superposed by the stronger emission from the inner shell. A maximum radial velocity of \(\pm 35 \text{ km s}^{-1}\) is observed at the center and decreases with distance to the central star. Emission from the outer shell can be recognized in the \(H\alpha\) line (Figure 6) by its spatial extend. However, the large thermal width and, probably, low expansion velocity in this line do not allow us to obtain detailed kinematic information. The outer shell cannot be recognized in the long-slit spectra of the \(H\alpha\lambda 6560\) line.

The inner shell can be identified at all slit positions in the three lines. The emission feature of the inner shell appears as a velocity ellipse in the PV maps. The size of the velocity ellipse is maximum at slit 8 with values of 30" in \(H\alpha\) and \([\text{N}\,\text{II}]\), and 20" in \(He\,\text{II}\). Maximum velocity splitting is observed at the center of the nebula (slits 3, 7, and 8) and amounts 60, 56, and 48 km s\(^{-1}\) in \(H\alpha\), \([\text{N}\,\text{II}]\), and \(He\,\text{II}\), respectively. This implies expansion velocities for the inner shell are of 30, 28, and 24 km s\(^{-1}\), respectively. Since we estimate an error of \(\leq 1 \text{ km s}^{-1}\) in our velocity measurements, these results show that the \(He\,\text{II}\) emission is confined to a slow expanding, inner thin layer of the inner shell while the \([\text{N}\,\text{II}]\) traces the outer layer that expands faster.

It is worth noting the very faint and wide emission observed in \([\text{N}\,\text{II}]\) (slit positions 2, 3, 7, and 8) located at about 12" and 8" to the north and south of the central star, respectively. The velocity of this faint emission spreads from \(\approx -45 \text{ to } 33 \text{ km s}^{-1}\). Comparing our \([\text{N}\,\text{II}]\) direct image and these particular PV maps, we identify these weak emissions with the two polar caps located on the main symmetry axis of the inner elliptical shell.

All slit positions in our \([\text{N}\,\text{II}]\) PV maps show the presence of at least one of the bright low-ionization knots identified in our optical \([\text{N}\,\text{II}]\) images (Figure 1, right panel). In all these PV maps, we can see that most of them are located very close to the zero position line, i.e., almost on the equatorial plane of the nebula. Although these PV maps show that emission arising from different bright knots may be mixed due to projection effects, we can estimate that their expansion velocity ranges between the inner and outer shell expansion velocities, 28 km s\(^{-1}\) to \(\approx 40 \text{ km s}^{-1}\), with only two of them having lower velocities, \(\approx 24 \text{ km s}^{-1}\). A final remark on the low-ionization knots is that in our \([\text{N}\,\text{II}]\) PV maps, slit positions 1 and 6, we can see two weak spots of emission almost symmetrically located at about 14" to the north and south from the central star, respectively. Both emission spots show negative and very low velocities of \(\approx -5 \text{ km s}^{-1}\). We identify these two spots of emission as coming from two bright knots that, in projection, appear to be located on the outer shell wall (see Figure 1, \([\text{N}\,\text{II}]\) images).

Although \([\text{N}\,\text{II}]\) emission from the two jet-like features can be identified at slit positions 2 and 5 (Figure 6), it can be better analyzed at slit positions 7 and 8 which were specially selected to cover these structures. In the corresponding PV maps, we can see the conspicuous emission arising from the two jet-like features. While the north jet-like feature emission is slightly redshifted, the south feature is slightly blueshifted. Both features show a small radial velocity, between 0 and 5 km s\(^{-1}\) which suggest that they are moving almost in the plane of the sky.

3. DISCUSSION

3.1. Morphokinematic Structure and Modeling

As we have described, NGC 7354 shows four different structures: two large-scale structures, the outer and the inner shells, the last having two polar caps located on its symmetry axis; a number of low-ionization bright knots lying about the equatorial plane, and two jet-like features located close to the north and south of the nebula, slightly inclined with respect to the inner shell symmetry axis. Our high-dispersion spectra indicate that (1) the inner shell is expanding with a velocity which is smaller than that of the outer shell; (2) most of the bright equatorial knots are moving at velocities closer to the outer shell; and (3) the jets’ projected velocity is very small.

In order to test the overall morphology and kinematic structure of the nebula we have used the interactive three-dimensional (3D) modeling tool SHAPE Ver. 2.0 (Steffen & López 2006). SHAPE produces synthetic images and PV diagrams which can be compared directly with our observed CCD images and PV maps. We have considered two ellipsoidal structures (inner and outer shells), two spherical sections (polar caps), several small spheres with different diameters (bright knots), and two geometrically thin cylinders of 2" in diameter (jet-like features). All these geometrical structures were slightly modified (smoothed, lengthened, and/or rounded) in order to match the overall look of our \([\text{N}\,\text{II}]\) images. In addition, all the structures were placed in the proper position to get the corresponding observed radial velocity from our PV maps. Figure 7 shows all the geometrical components used to construct our SHAPE model.

Each one of the main structures was analyzed separately in order to obtain its spatial velocity independently. Due to projection effects, we are unable to distinguish neither if the low-ionization knots are located between the inner and outer shells.
nor if they are lying on the foreground or on the background side of the nebula. Thus, we have assumed that the bright knots are located on the outer shell wall, according to their individual velocity shown in our PV map. It is important to remark that the inclination angle of the different structures is unknown and shape does not solve it. Final geometrical and kinematic parameters are shown in Table 5. Some of the inner shell basic parameters can be compared to those found by Hajian et al. (2007) with an extended prolate ellipsoidal shell model. While our derived inclination and P.A.s are consistent with the ones determined by Hajian et al. (2007), our expansion velocity value is larger than theirs. However, as they have found in all the cases examined in their study, the [N ii] gas has a larger expansion velocity than the [O iii] gas. Then, since we have determined the expansion velocity through the [N ii] line emission, a difference in expansion velocities is expected. Distance estimations found in the literature lie around 1.2 kpc (Cahn et al. 1992; Zhang 1995; Phillips 2004), 1.5 kpc being the largest estimation (Sabbadin 1986) and 0.88 kpc the smallest one (Daub 1982). We have adopted the largest value of 1.5 kpc in order to derive an upper limit for the kinematical ages. However, using a distance value of 1.2 kpc implies a decrease in the kinematical age estimation.
of only 20%. But most important, distance uncertainty does not modify the proposed chronological sequence of structure formation in our model.

From this model, we have obtained synthetic images and PV diagrams which strongly resemble the observed ones; see Figure 8 for an example of this good match. Thus, from the proposed 3D model we have not only reproduced qualitatively the overall morphology of NGC 7354 but we have also quantitatively reproduced the kinematic behavior of each structure.

3.2. Formation of NGC 7354

At present, binary star models have been successful in explaining the origin and process responsible for the equatorial density enhancement required in the interacting stellar wind (ISW) model, or rather the generalized ISW (GISW) model, to explain early- and middle-type elliptical and even bipolar large-scale structures observed in PNe (e.g., Balick et al. 1987; Mellema 1995; Mellema & Frank 1995). On the one hand, common envelope (CE) evolution in close binaries has been proposed to be responsible for the expanding slow wind torus needed in GISW (e.g., Rasio & Livio 1996; Frank et al. 1996; Terman & Taam 1996; Sandquist et al. 1998). On the other hand, accretion disks in binary systems seem to account for the narrow waist bipolar morphologies and even the jets present in PNe. Details may vary in each binary model in order to explain individual morphologies and structures, but in all of them the main idea is that of a jet launched by the central star, or its companion (Soker & Rappaport 2000; García-Arredondo & Frank 2004; Sahai et al. 2007; Dennis et al. 2008; Akashi & Soker 2008, among others).

Since at first glance NGC 7354 looks like a rather elliptical nebula, one may think that the single-star models (ISW or GISW) can explain the presence of the outer and inner shells, and even the formation of the two jet-like features observed in our [N II] image (Balick et al. 1987). However, it is unable to explain why all the different structures show different P.A.'s on the sky. This characteristic may indicate that the direction of ejection varies with time, and more likely that all the features were formed as independent events. Although nowadays there is no evidence of NGC 7354 possessing a binary nucleus, one can take a look at binary star models to try to understand in a consistent way the observed morphology of NGC 7354.

It has been proposed that the GISW model coupled with the predictions of the CE evolution theory can account for the formation of elliptical and even bipolar PNe morphologies (Soker & Livio 1994). Then, we could successfully explain the outer and inner shells in NGC 7354 based on this mixed model in the following way. After the CE phase has ended, i.e.,
the envelope has been ejected, the binary may become closer, mass transfer takes place, an accretion disk is formed, and a jet may be launched (Soker & Livio 1994). If we assume that the subsequent evolution is similar to those described in the models for PNe (Soker & Rappaport 2000; Lee & Sahai 2003; Dennis et al. 2008; Akashi & Soker 2008), it is possible that a jet arises from an accretion disk. Then, the accretion disk theory would be able to explain also the two jet-like features observed in NGC 7354. Moreover, some of these models even propose the formation of an expanding dense ring in the equatorial plane (Soker & Rappaport 2000) which in the case of NGC 7354 might be related to the equatorial bright knots. As the nebula evolves, a combination of the processes and mechanisms just mentioned might take place.

With this in mind, we suggest a possible qualitative scenario for the formation of the main structures present in NGC 7354. A slow wind is lost by a central binary system undergoing a CE phase, producing the mild elliptical outer shell. When the AGB fast wind begins, it finds an equatorial density enhanced environment forming the bright elliptical rim or inner shell. At this point, the CE has been completely ejected and mass transfer from the secondary (main-sequence star) into the primary (white dwarf) will form an accretion disk and eventually a couple of jets will be launched. Once the jets have appeared, they will “push” the polar ends of the inner shell, detaching them from it. Eventually, the two jets would break the caps and escape from the main body of the nebula. Along with the processes mentioned, the binary system may be precessing, and each of

Table 5

| Geometrical Structure | Size (") | Expansion Velocity (km s\(^{-1}\)) | Inclination Angle \(i\) (deg) | Position Angle \(\phi\) (deg) | Kinematical Age (yr) |
|-----------------------|----------|---------------------------------|-----------------------------|---------------------------|---------------------|
| Outer elliptical shell| 16 × 15  | 45                             | 94                          | 18                        | 2500                |
| Inner elliptical shell| 10 × 8   | 35                             | 94                          | 28                        | 1600                |
| Semispherical cap N   | 14       | 47                             | 94                          | 28                        | 1000                |
| Semispherical cap S   | 14       | 47                             | 85                          | 203                       | 1000                |
| Spherical knots       | 1–2      | 25–44                          | ...                         | ...                       | ...                 |
| Thin cylinder N       | 7        | 60                             | 95                          | 3                         | 1900                |
| Thin cylinder S       | 13       | 60                             | 85                          | 205                       | 1900                |

Notes. Size refers to major and minor axes in the case of elliptical structures, length for thin cylinders, and diameter in the case of the spherical knots and polar caps. All kinematical ages were determined assuming a distance to the nebula of 1.5 kpc (Sabbadin 1986).
the structures would show a different P.A. on the sky. In the case of the two jets, precession may cause them to impinge on the polar caps at a certain angle, i.e., not along the symmetry axis of the caps, apparently breaking them on their “base”. According to our derived kinematical ages, the chronological sequence of formation seems to be consistent with the above description. The outer shell is the oldest structure present in the nebula with an age of about 2500 years. The next oldest structure would be the inner elliptical shell at ≃1600 years. Kinematical ages for the two jet-like features indicate that they are coeval, and both were formed almost at the same time as the inner elliptical shell. However, we should note that the age was derived assuming that they have been moving with the same velocity (60 km s$^{-1}$) since their launch. According to the theory of formation of jets, this low initial velocity would be very unlikely, since they arise from accelerated flowing material. It is, more likely that the jets possessed a higher initial velocity but have been restrained along their way. The main cause of this deceleration may have been the interaction of the jets with the polar caps.

Regarding the equatorial low-excitation bright knots, as we have mentioned above, they may be related to the dense expanding ring formed around the binary system. The bright knots show velocities ranging between the inner and outer shell expansion velocities. This may indicate that they are moving with a similar velocity as the particular ambient gas in which they are embedded. We may compare these bright knots with the microstructures observed in NGC 2392 (Eskimo Nebula; O’Dell et al. 2002) and NGC 7662 (Perinotto et al. 2004b). Although each one of these nebulae is seen with a different view angle (NGC 2392 is seen in pole-on and NGC 7662 is seen in edge-on) both of them show various low-ionization knots located beyond the inner structure and mainly on the outer envelope. If we compare the general morphology of NGC 7354 with that observed in NGC 2392 and NGC 7662, one can see that the three of them show an ellipsoidal inner structure surrounded by an outer envelope, with low-ionization bright knots located on the outer structure, plus jet-like features, interpreted as FLIERs in the case of NGC 7662. In the case of NGC 7354, since it is observed with an edge-on view angle and it is inclined with respect to the plane of the sky, we are not able to observe the real morphology of the equatorial bright knots. However, one can imagine that if one could get a pole-on view, i.e., with the inner shell major axis aligned with our line of sight, one would see bright knots located in a zone between the inner and outer shells very like the arrangement of knots with tails observed in the Eskimo Nebula. Therefore, having all these elements together, we suggest that, as in the cases of NGC 7662 and NGC 2392, the equatorial bright knots observed in NGC 7354 are not spherical structures but knots with tails, or even filamentary structures. This last suggestion is strongly supported by the high-resolution [N II] HST image, Figure 2.

A full model with MHD simulations is beyond the scope of the present study, but we are aware that it could clarify some aspects of our work.

4. CONCLUSIONS

We have carried out a detailed morphological and kinematical analysis of the PN NGC 7354. In addition, we have derived the physical conditions and elemental abundances in 21 regions of the nebula. The main conclusions of this work can be summarized as follows.

Physical parameters of all the different structures show that there are slight variations, both in electron density and electron temperature, within the nebula. Considering our error estimates, density seems to slightly increase inward from the outer shell border to the interior of the inner elliptical shell, and temperature values also seem to slightly increase in the same direction. Equatorial bright knots are clearly denser than both shells with temperatures in the typical range for ionized gas. Both jet-like features present a quite low-density value and temperature was only determined for the south jet-like feature. All our derived physical parameter values are consistent with the ones expected for radiatively excited gas. Local extinction values within the nebula show a slight increasing gradient going from south to north of the nebula and from west to east along the location of the equatorial knots.

Based on our kinematical data, we have obtained a model that consistently reproduces the overall as well as the detailed morphology and PV maps of the nebula, using the 3D interactive tool SHAPE. The final geometrical components included in the model are: (1) two shells with similar inclination angles (with respect to our line of sight) but different P.A.s of the projected semimajor axis, (2) two semispherical caps placed on the top of the inner elliptical shell, (3) 13 spherical knots with different sizes whose velocities spanned between the corresponding velocity values for the outer and inner shells, placed at different positions on the outer shell surface according to the optical image and observed spectra, and (4) two geometrically thin cylinders corresponding to north and south jet-like features.

Finally, although there is no evidence of binarity in NGC 7354 at present, we suggest a qualitative scenario for the formation of the different structures in the nebula based on the theory of CE evolution and formation of accretion disks in binary systems found in the literature.

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