MULTIPLE AND PRECESSING COLLIMATED OUTFLOWS IN THE PLANETARY NEBULA IC 4634

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ABSTRACT

With its remarkable double-S shape, IC 4634 is an archetype of point-symmetric planetary nebulae (PNe). In this paper, we present a detailed study of this PN using archival HST WFPC2 and ground-based narrowband images to investigate its morphology, and long-slit spectroscopic observations to determine its kinematics and to derive its physical conditions and excitation. The data reveal new structural components, including a distant string of knots distributed along an arclike feature 40°–60° from the center of the nebula, a skin of enhanced [O III]/Hα ratio enveloping the inner shell and the double-S feature, and a triple-shell structure. The spatio-kinematical study also finds an equatorial component of the main nebula that is kinematically independent of the bright inner S-shaped arc. We have investigated in detail the bow shock–like features in IC 4634 and found that their morphological, kinematical, and emission properties are consistent with the interaction of a collimated outflow with surrounding material. Indeed, the morphology and kinematics of some of these features can be interpreted using a three-dimensional numerical simulation of a collimated outflow precessing at a moderate, time-dependent velocity. Apparently, IC 4634 has experienced several episodes of point-symmetric ejections oriented in different directions, with the outer S-shaped feature being related to an earlier point-symmetric ejection, and the outermost arclike string of knots being the relic of a still much earlier point-symmetric ejection. There is tantalizing evidence that the action of these collimated outflows has also taken part in the shaping of the innermost shell and inner S-shaped arc of IC 4634.

Subject headings: planetary nebulae: general — planetary nebulae: individual (IC 4634) — stars: winds, outflows

1. INTRODUCTION

Planetary nebulae (PNe) represent the final phases of the stellar evolution of low- and intermediate-mass stars. The shape of a PN is thought to be determined by the interaction of the current fast, tenuous stellar wind (e.g., Patriarchi & Perinotto 1991) of its central star with the previous slow, dense wind of its asymptotic giant branch (AGB) phase. In the so-called interacting stellar winds (ISW) model of PN formation (Kwok et al. 1978), the critical parameter is the density distribution of the AGB wind (Balick 1987): a spherical symmetric AGB wind will result in a spherical PN, while a polar density gradient in the AGB wind will result in an elliptical or bipolar PN, depending on the degree of the density gradient.

This simplified view of PN formation has been challenged by the overwhelming body of observations of PNe showing small-scale features (e.g., NGC 7662; Perinotto et al. 2004), collimated bipolar outflows (e.g., NGC 7009; Fernández et al. 2004), and point-symmetric morphologies, including multiple point-symmetric bubbles (e.g., Hen 2-47 and M1-37; Sahai 2000) and point-symmetric collimated outflows (e.g., NGC 6884; Miranda et al. 1999). All these features are difficult to interpret in the framework of the ISW model and have inspired new theoretical ideas to explain the shaping of PNe. New scenarios of PN formation and shaping include magnetic collimation (García-Segura &
The images were acquired through filters that included the HST 2.5m Nordic Optical Telescope (NOT) of the Roque de los Muchachos Observatory (La Palma, Spain) on 2005 August 1. The images were acquired through filters that included the Hα (λc = 6563 Å, FWHM = 9 Å, texp = 900 s) and Hα + [N ii] (λc = 6562 Å, FWHM = 46 Å, texp = 1800 s) emission lines using the Andalucia Faint Object Spectrograph and Camera (ALFOSC) camera in imaging mode. The detector was an E2V 2K × 2K CCD with a pixel size of 13.5 μm, providing a plate scale of 0.19” pixel−1 and a field of view of ~6.5”. The angular resolution during the observations, as derived from the FWHM of stars in the field of view, was 0.8”–0.9”.

2.2. Echelle Observations

High-dispersion spectroscopic observations of the Hα and [N ii] λ6548, 6584 lines of IC 4634 were obtained using the echelle spectrograph on the 4 m Blanco Telescope of the Cerro Tololo Inter-American Observatory (CTIO) on 2002 June 22. The spectrograph was used in long-slit mode to obtain single-order observations of the Hα and [N ii] λ6548, 6584 lines. The unvignetted slit length was ~3”. The 79 line mm−1 echelle grating and the long-focus red camera were used, resulting in a reciprocal dispersion of 3.4 Å mm−1. The data were recorded with the SITE 2K No. 6 CCD, with a pixel size of 24 μm. This configuration provided a spatial scale of 0.26” pixel−1 and a sampling of 3.7 km s−1 pixel−1 along the dispersion direction. The slit width was set to 0.9”, and the resultant instrumental resolution (FWHM) was 8 km s−1. The angular resolution, determined by the seeing, was ~1.0”. The echelle observations were made with the slit placed at the central star of IC 4634 and oriented along the position angles P.A. = 60° (texp = 1050 s), 120° and 180° (texp = 900 s), and 150° and 166° (texp = 1200 s).

High-dispersion spectroscopic observations of the Hα, [N ii] λ6584, and [O iii] λλ5007 lines were also obtained using the IACUB spectrograph (McKeith et al. 1993) on the 2.5 m NOT of the Roque de los Muchachos Observatory on 2004 June 29. The spectrograph was used in the long-slit mode to obtain single-order observations of the Hα and [N ii] λ6584 lines in the 9th order, and of the [O iii] λλ5007 line in the 11th order. IACUB provides a reciprocal dispersion of 1.74 Å mm−1 in the 9th order and 1.43 Å mm−1 in the 11th order. The data were recorded with a Thomson CCD with a pixel size of 19 μm. This configuration provided a spatial scale of 0.139” pixel−1, a sampling along the dispersion direction of 1.5 km s−1 pixel−1 for the spectrum of the Hα and [N ii] λ6584 lines, and of 1.6 km s−1 pixel−1 for the spectrum of the [O iii] λλ5007 line. The unvignetted slit length was 40”, and the slit width was set to 0.65”, resulting in an instrumental resolution (FWHM) of 9.5 km s−1 for the Hα and [N ii] λ6584 lines, and 8.5 km s−1 for the [O iii] λλ5007 line. The angular resolution, determined by the seeing, was ~0.8”. The echelle observations of the Hα and [N ii] λ6584 lines were made along a slit offset 2” west and 46.4” north of the central star of IC 4634, and oriented along P.A. = 0° (texp = 1200 s). The echelle observations of the [O iii] λλ5007 line were made along a slit placed at the central star of IC 4634 and oriented along P.A. = 150° (texp = 1800 s).

2.3. Medium-Dispersion Spectroscopic Observations

Medium-dispersion long-slit spectroscopic observations of IC 4634 were obtained using the Boller & Chivens spectrograph on the 2.1 m telescope of the Observatorio Astronómico Nacional de San Pedro Mártir (Baja California, Mexico) on 2002 June 16, and 2004 May 20 and August 12. Multiple observations were obtained at several slit positions as listed in Table 1. In all cases, the 400 line mm−1 grating was used, the slit length was 5”, and its width was set to 150 μm, projecting to 2” on the sky. The data were recorded on a SITE3 1K CCD with a pixel size of 24 μm. This configuration provided a spatial scale of 1.05” pixel−1.
and a spectral scale of 3 Å pixel$^{-1}$, with a spectral coverage from 4240 to 7310 Å. The long-slit spectra were reduced and calibrated following standard procedures using the XVISTA package.$^2$ For the wavelength calibration, we used a He-Ar lamp. The spectral resolution was $\sim$6.8 Å. For the flux calibration, several standard stars were observed each night.

3. STRUCTURAL COMPONENTS OF IC 4634

The HST narrowband images and ratio maps of IC 4634 shown in Figure 1 reveal a wealth of structural components in this nebula. In Figure 1, we have labeled the most prominent structures in IC 4634:

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$^2$ XVISTA was originally developed as Lick Observatory Vista. It is currently maintained by Jon Holtzman at New Mexico State University and is available at http://ganymede.nmsu.edu/holtz/xvista.
A bright inner shell (IS), surrounded by a dim outer shell (OS).

An inner S-shaped feature formed by two knotty point-symmetric arcs (D-D') that present distinct properties along the minor axis of IS (Dm-Dm').

An outer S-shaped feature formed by two pairs of bow shock–like structures (A-A' and B-B') along different position angles and located at different distances from the central star.

A pair of bow shock–like structures, C-C', along P.A. \(\sim 120^\circ\).

A skin of enhanced [O iii]/H\(\alpha\) ratio (S) that encloses the inner shell and bow shock–like structures.

An outer envelope (Env) surrounding all previous components, where some individual features (F-F' and G) can be distinguished.

A string of knots (H) distributed along an arclike feature \(\sim 40''\) north of IC 4634 and accompanied by diffuse emission (Hd).

In the following, we will describe in greater detail the morphology, kinematics, excitation, and physical conditions of the different structural components present in IC 4634.

The H\(\alpha\) fluxes, and measured and intrinsic line-intensity ratios of the emission lines detected in the medium-dispersion spectra in regions IS, A-A', and D-D' are listed in Table 2. The H\(\alpha\)-to-H\(\beta\) ratio measured in the medium dispersion spectra and in the HST images implies an extinction coefficient \(C_{H\beta} = 0.34\). The HST H\(\alpha\)/H\(\beta\) ratio map indicates that there are no significant extinction variations across IC 4634. The measured line-intensity ratios have been dereddened accordingly using the wavelength-dependent extinction law from Savage & Mathis (1979). The plasma diagnostics (\(T_e\) and \(N_e\)), and ionic and elemental abundances listed in Table 3 were derived from the intrinsic line-intensity ratios listed.
in Table 2 for the different regions of IC 4634 using the nebular abundance package ELSA (Johnson et al. 2006).

### 3.1. The Inner Shells of IC 4634

From the center outward, the first component of IC 4634 is the inner shell, IS, around the central star. This inner shell has a size of 2.5′′ × 5.2′′ and a major axis along P.A. = 150°. The edge of the inner shell is sharp, and its surface brightness is enhanced with respect to the shell interior. This morphology suggests a thin shell, although it must be noted that an intricate pattern of filaments is superimposed on the shell. The shell brightness is also notably enhanced along its minor axis, marking a bright equatorial belt. The shape of the inner shell can be roughly described as elliptical (Fig. 2), but at the tips of its major axis several protrusions of different sizes extend outward. Further distortion of the shell shape is introduced by the bending of the shell edge at its equator, causing the edge of the inner shell along its major axis to show a subtle S-shape. It is worth noting that the central star of IC 4634 is not located at the exact center of the shell, but is displaced by ~0.20″ toward the south.

The echellogram of the [O iii] emission line along the major axis of the inner shell at P.A. = 150° (Fig. 3) reveals a prolate expanding shell with an expansion velocity at the position of the central star of 15.3 km s\(^{-1}\). The systemic radial velocity in the local standard of rest (LSR) system is ~20.1 km s\(^{-1}\), in agreement with other estimates (e.g., Durand et al. 1998). The line tilt is small, indicating a low inclination of the shell with respect to the plane of the sky, but the S-shaped pattern of the line suggests accelerating features at the tips of the shell major axis. These blowout structures correspond to the protrusions observed at the tips of the major axis of the shell, with the northwest protrusion receding from the observer and the southeast protrusion approaching. The echellogram of the [N ii] emission line along the major (P.A. = 150°) and minor (P.A. = 60°) axes (Fig. 3) also reveals an expanding shell, but its kinematics cannot be studied in detail in this line, because the bright emission from the adjacent D-D′ and Dm-Dm′ regions overwhelms the emission from IS. The expansion velocity at the position of the central star is illustrated in the [N ii] echellogram along the minor axis by an ellipse with a spatial semiaxis ~1.3″ and an expansion velocity of 18 km s\(^{-1}\). In the Hα echellogram along the major axis of IC 4634, also shown in Figure 3, the thermal broadening of the line is larger than the line split, and no shell can be clearly identified.

The inner shell of IC 4634 is the region where the [N ii] / Hα ratio map (Fig. 1) shows its lowest value, ~0.04. The high excitation is confirmed by the [N ii] / Hα line ratio map presented in Figure 3, which shows this ratio to be nearly zero in the central regions of IC 4634. The [O iii] / Hα ratio (Fig. 1) is very flat in this region, with a typical dereddened value of ~3.0. This is also the only region where emission lines of He ii are detected in the low-dispersion spectra (Table 1), although the intensities of these lines are low, with I(He ii 4686 Å)/I(Hβ) ~ 0.005. Aside from the [Ar iv] λλ4715, 4740 lines, no other high-excitation lines are present in the spectrum of the inner shell of IC 4634. The [Fe iii] λ5270 emission line and the Wolf-Rayet complex of C iv λλ5801-12 are weakly detected in this spectrum.

The electron density and temperature of the inner shell of IC 4634 can be derived using the density-sensitive [S ii] λλ6716, 6731 doublet line ratio and the temperature-sensitive [N ii] and [O iii] auroral-to-nebular line ratios. Using the line intensities listed in Table 2, we have computed an electron density of...
from the \([\text{S} \text{ ii}]\) line ratios, and electron temperatures of 13,000 K from the \([\text{N} \text{ ii}]\) lines and of 10,000 K from the \([\text{O} \text{ iii}]\) lines. These values are consistent with previous estimates of the physical conditions in the central region of IC 4634 (Aller & Czyzak 1983; de Freitas Pacheco et al. 1992; Hyung et al. 1999), which also find higher electron temperatures from the \([\text{N} \text{ ii}]\) lines than from the \([\text{O} \text{ iii}]\) lines. The nebula does not show any evidence of N or He enrichment; thus, it can be classified as a type II PN based on its chemical abundances (Peimbert 1978).

The inner shell of IC 4634 is surrounded by a faint shell of radius 300, best seen at P.A. = 85°–150° and 265°–330° (Fig. 2), known as the outer shell OS, as marked in Figure 1. At other position angles, the low surface brightness of this shell is overwhelmed by the bright \(D-D'\) and \(Dm-Dm'\) features. The visible portion of OS suggests that it is round, or at least less aspherical than the innermost IS.

### 3.2. The Inner Point-symmetric Structure

One of the most prominent features in IC 4634 is the pair of low-excitation arcs that we have named \(D-D'\) in Figure 1. A close-up of these features is presented in Figure 4. \(D-D'\) have a point-symmetric morphology, bending around IS in arclike features that extend from the IS equator, at P.A. ~ 60° (240°), to the IS tips, at P.A. ~ 330° (150°). These features do not look like filaments, but rather like broad (≥1°) clumpy strips, particularly in the \([\text{N} \text{ ii}]\) image. The morphology is reminiscent of the low-excitation polar caps of NGC 6543 (Miranda & Solf 1992; Balick 2004) and of the south fuzz of NGC 2392 (O’Dell et al. 2002).
The surface brightness of these structures does not change significantly in the [N II] line, but there is a clear enhancement of the Hα and [O III] emission in the equatorial regions that we denote as Dm-Dm'. To investigate these changes in more detail, we have used the well-established [O III]/Hα versus [N II]/Hα diagnostic diagram. To construct this diagram, we selected the rectangular regions encompassing D-D' and Dm-Dm' shown in Figure 5 (right), and computed the reddened [O III]/Hα and [N II]/Hα ratios at every pixel with a surface brightness above a threshold value of 3σ. The resulting values are plotted in the [O III]/Hα versus [N II]/Hα diagrams shown in Figure 5 (left). In these diagrams, D and D' present very similar distributions in their excitation conditions, and the same applies between Dm and Dm'. These show slightly higher [O III]/Hα values than D-D', but very different [N II]/Hα distributions, with Dm-Dm' having values lower than ~0.15, while D-D' present values of this ratio up to 0.6. Therefore, there is a notable segregation in the [O III]/Hα versus [N II]/Hα plane between D-D' and Dm-Dm', indicating different excitation conditions.

The different natures of D-D' and Dm-Dm' are further substantiated by their kinematics in the [N II] echellogram at P.A. = 60° (Fig. 3). In this echellogram, four distinct compact knots are detected at the locations of D-D' and Dm-Dm'. Of these four knots, pairs of knots located on the same side of the nebula have opposite velocities; i.e., D and Dm have very similar locations, but very different radial velocities, and the same applies to D' and Dm'. The position-velocity (PV) map of the [N II]/Hα ratio (Fig. 3) shows that the brighter two [N II] knots, which correspond to D-D', have lower excitation, while the two fainter knots, which can be identified with Dm-Dm', show higher excitation. Therefore, D and Dm' are blueshifted, with systemic radial velocities of ~21 and ~27 km s⁻¹, respectively, while D' and Dm are redshifted, with systemic radial velocities of +21 and +27 km s⁻¹, respectively.

The kinematics along D-D' has been further mapped at P.A. = 150°, 166°, and 180°. In the corresponding echellograms, D-D' appear as bright, compact knots, with a FWHM velocity of ~18 km s⁻¹ in the [N II] λ6584 line. D is blueshifted, and its radial velocity shows small variations along this structure, as shown in Figure 4. D' is redshifted and shows velocity variations symmetric to those presented by D. It must be noted that these velocities are opposed to the line tilt shown by the inner shell, whose northwest protrusion is redshifted, while its southeast tip is blueshifted.

The physical conditions at the tips of D-D' have been derived using temperature- and density-sensitive line ratios obtained from the medium-dispersion spectroscopy. Using the line intensities listed in Table 2, we computed an electron density of 3800 cm⁻³ for D and 5200 cm⁻³ for D'; i.e., the density of D-D' is 2–3 times lower than the density of the inner shell. The [N II] electron temperature is found to be 11,500 and 10,200 K for D and D', respectively. The [O III] electron temperature is 10,500 K for D and 10,000 K for D'.

### 3.3. The System of Bow Shock-like Structures

The system of bow shock–like structures observed at P.A. ~ 150° (A-A'), ~166° (B-B'), and ~120° (C-C') is one of the most remarkable features of IC 4634. There are very few examples of bow shock structures among PNe (e.g., IC 4593; Corradi et al. 1997). In the following subsections, we describe in further detail the structure, excitation, physical conditions, and kinematics of these features.

#### 3.3.1. Small-Scale Structure

The Hα, [N II], and [O III] composite pictures of A and A' shown in Figure 6 reveal a wealth of small-scale structures in these features. The bow shock–like feature A lies 10° northwest (NW) of the central star. The counter–bow shock (feature A') is precisely symmetrical, on the opposite side of the central star (see Fig. 1). A chain of knots extends toward the SE from structure A and toward the NW from structure A', ending in a smaller...
sized bow shock labeled $B$ and $B'$ in the NW and SE, respectively, which lies $\sim 7''$ from the central star of IC 4634. There are well-defined bow-shaped structures with sharp edges that emit predominantly in [O iii] both in $A$ and $A'$ (shown in blue in Fig. 6, top). Fainter [O iii], [N ii], and H$\alpha$ diffuse emission is observed in the region between the bow shock and the inner nebula. In the brightest regions of $A$ and $A'$, several knots can be resolved that appear distinct in [N ii] (Fig. 6) but that are surrounded by diffuse emission in [O iii]. The twisted distribution of these [N ii] knots is indicative of the development of instabilities at this location.

The bow shock structures $B$ and $B'$ show faint wings that are also more prominent and extended in the [O iii] image. Only one knot, located at the cap of the bow shock structure, is resolved within $B$. The [O iii] image shows that the spatial distribution of this knot is considerably more extended than the corresponding H$\alpha$ and [N ii] intensity peaks. In the emission-line images of the counter–bow shock $B'$, three knots are resolved.

$C$ and $C'$ (Fig. 1) are a pair of low-emissivity features located along an axis at P.A. $\sim 120^\circ$. In the [N ii] image, they show pointed, triangular tips surrounded by round, caplike structures in the [O iii] and H$\alpha$ images. At the outermost skin of these cap-like structures, the [O iii]/H$\alpha$ line ratio is enhanced.

3.3.2. Excitation and Physical Conditions

The [O iii]/H$\alpha$ and [N ii]/H$\alpha$ ratio maps show abrupt changes in these line ratios throughout $A-A'$, $B-B'$, and $C-C'$ (Fig. 6). At the leading edge of the bow shock structures, the [O iii] emission
is enhanced, with [O iii]/Hα values of 2–3. At the brightest regions of A–A’ and B–B’ (i.e., at the emitting knots of the bow shock structure), the [O iii]/Hα ratio declines to 1–1.5, while the [N ii] emission is enhanced, with [N ii]/Hα values of 0.8–0.9, significantly raised from the value of 0.05–0.15 behind the bow shock. Similarly, there are abrupt changes in these ratios across the B–B’ features (Fig. 6), with the lowest [O iii]/Hα ratios and the highest [N ii]/Hα ratios at the location of the knots (i.e., at the head of the bow shock). The spatial offset between the [O iii]-enhanced cap-shaped bow shocks and the low-ionization [N ii] bright knots is 0.3”. We note that the wings at the A–A’ bow shocks show the highest excitation among these structures, with [O iii]/Hα values of ~4, and [N ii]/Hα values lower than ~0.2.

As in § 3.2, we have computed the [O iii]/Hα versus [N ii]/Hα diagrams for the different rectangular regions encompassing A–A’, B–B’, and C–C’ shown in Figure 5 (right). In these diagrams, shown in Figure 5 (left), note the strong similarity between the distribution of the data points of each structure in the NW and SE regions. Data points from structures A–A’ and B–B’ tend to occupy an extended region in Figure 5 (left), implying large variations in the excitation conditions on small scales. Most points fall in the region of the diagram where [O iii]/Hα ~ 2–3 and [N ii]/Hα ~ 0.05–0.20, which corresponds to the gas behind the bow shock. There is a locus of points in this diagram characterized by low values of [O iii]/Hα and large values of [N ii]/Hα, which correspond to the bright emitting knots. On the other hand, there are also points characterized by large values (≥3) of [O iii]/Hα and very low values of [N ii]/Hα; these points correspond to the “skin” of [O iii] observed at the leading edge of the knots. The excitation of the bow shock—like structures B–B’ is similar to that of A–A’. Most of the data points of B–B’ fall in the region where [O iii]/Hα is in the range 2–3 and [N ii]/Hα ranges from 0.05 to 0.20. The points with low [O iii]/Hα and high [N ii]/Hα values correspond to the [N ii] bright knots. Note the presence of several data points with large [O iii]/Hα values (ranging from 3 to 4), which correspond to the leading edge of the bow shocks.

The data points from features C–C’ occupy a small region in the [O iii]/Hα versus [N ii]/Hα diagram (Fig. 5, right). Most points fall in the region with large [O iii]/Hα (~2.25–3.5) and low [N ii]/Hα (~0.15). Data points corresponding to the outer skin of [O iii] show [O iii]/Hα larger than 3.5. There are noticeable differences between the distribution of the data points of A–A’ and B–B’ in the [O iii]/Hα versus [N ii]/Hα diagram and that of C–C’. In particular, the data points of C–C’ have a smaller scatter in the [O iii]/Hα versus [N ii]/Hα diagram than those of A–A’ and B–B’, implying small variations in the excitation conditions across C–C’. Moreover, C–C’ have higher excitation than A–A’ and B–B’.

Our ground-based medium-dispersion spectroscopy (Table 2) cannot resolve the rapidly changing ionization structure seen in the HST images, but the use of additional line diagnostic diagrams from a variety of emission-line ratios can provide further information on the excitation and physical conditions of A–A’. To better compare the overall excitation of A–A’ with that of the inner shell (IS) and D–D’, the line diagnostic diagrams shown in Figure 7 also include emission-line ratios from these regions. The spectra of A–A’ show enhanced emission of low-excitation lines: the relative intensities of [O i], [O iii], [N ii], and [S ii] are up to 10 times higher than those in the spectrum of IS, while the relative intensities of [O i], [N ii], and [S ii] are larger than those of D–D’ by a factor of ~2. The intensity of the [O i] lines of both A–A’ and D–D’ is only 10%–15% lower than those of the IS, while the He λ and [Ar iii] lines have similar intensities among these different regions, indicating that the radiation field reaching both A–A’ and D–D’, modified by the absorption in the IS, is similar in both cases and capable of ionizing species with ionization potential ≤30 eV. We have obtained the [O iii]/[O i] intensity ratio, which is indicative of the ionizing parameter for a photoionized gas, for the three different regions. The largest value (i.e., the largest ionizing parameter) corresponds to the inner shell, as expected, with a value of ~250. A–A’ and D–D’ show lower values in the narrow range from ~70 to ~80, thus indicating that these structures have similar local ionizing conditions (somewhat lower in A–A’). Even though the ionizing parameters are similar in D–D’ and A–A’, the latter shows stronger emission of low-excitation lines (see above), indicating shock excitation.

Figure 7 also reveals the progressive change in the [N ii] and [O iii] temperatures with distance from the central star of IC 4634: the [N ii] 6584/5755 emission-line ratio increases (and so the temperature inferred from this line ratio decreases) from IS to A–A’, while the [O iii] 5007/4363 emission-line ratio decreases (and so the temperature derived from this line ratio increases) as we move outward from regions of low [N ii]/Hα values at IS to regions with larger values of this ratio. The electron temperatures of A and A’ are, respectively, 10,200 and 12,200 K from the [N ii] lines, and 10,800 and 11,400 K from the [O iii] lines. Similarly, the electron density from the [S ii] doublet line ratio is found to be 2800 cm−3 in A and 1500 cm−3 in A’, i.e., 3–7 times lower than in IS.

3.3.3. Kinematics

The large opening angle of these bow-shock–like structures (A and A’ have almost flat morphologies) suggests a low inclination angle with the plane of the sky. This is confirmed by the PV diagrams of the bow shock–like structures A–A’ and B–B’ displayed in Figure 8, which show low radial velocities with respect to the systemic velocity: ±20 ± 3 km s−1 for A–A’ and B–B’, respectively. The Hα and [N ii] λ6584 echellogram along P.A. = 120° (not shown in Fig. 8) shows faint emission from C and C’ moving at radial velocities with respect to the systemic velocity.
velocity of \( \pm 30 \) km s\(^{-1}\). We note that \( A, B, \) and \( C(A', B', \) and \( C') \) are receding from (approaching) us, with motion opposite that of \( D(D') \).

It is also interesting to note the detailed line shape in the PV diagrams of Figure 8 at \( A-A' \) and \( B-B' \). At the location of \( A-A' \), the \( \text{H} \alpha \) and \( [\text{O iii}] \) emission lines are wedge-shaped, with the widest side at the line tip (the leading edge of the bow shock), while the \( [\text{N ii}] \) line shape is nearly round. The FWHM of the \( \text{H} \alpha \) emission line of both \( A \) and \( A' \) increases from \( \sim 30 \) km s\(^{-1}\) at the narrow end of this wedge-shaped feature to \( \sim 70 \) km s\(^{-1}\) at its wide end. A close examination of the \( \text{H} \alpha \) and \( [\text{O iii}] \) PV diagrams reveals a velocity gradient at the leading edge of \( A-A' \), whereas the velocities in the region behind the bow shock seem rather constant. The lowest velocities are found at the leading edge of the bow shock, facing away from the central star of IC 4634, where the radial velocity of the \( \text{H} \alpha \) line decreases \( \sim 10 \) km s\(^{-1}\) within \( 1'' \). Across \( B-B' \), the radial velocity is roughly constant. The \( \text{H} \alpha \) emission-line profiles show a mean FWHM of \( \sim 40 \) km s\(^{-1}\). The emission ends in a sharp drop at the outer edge of \( B-B' \).

Finally, the string of \( [\text{N ii}] \) knots that arises from the edge of the \( A \) and \( A' \) bow shocks may be suggestive of a trail of material left in their wakes as they moved forward. Indeed, the radial velocity in the outer low-ionization arcs shows an abrupt change from the bow shock structure to the linear string of knots, suggesting a deceleration. We will show in § 4.2 that the interaction between a precessing collimated outflow with time-dependent velocity and the surrounding medium offers an alternative explanation to the string of \( [\text{N ii}] \) knots.

### 3.4. The \( [\text{O iii}] \) Skin

It has been mentioned that the \( \text{[O iii]}/\text{H} \alpha \) ratio is clearly enhanced in caplike structures just outside the bow shocks \( A-A', B-B', \) and \( C-C' \). The \( \text{[O iii]}/\text{H} \alpha \) ratio map (Fig. 1, middle right) reveals that these \( [\text{O iii}] \)-enhanced caplike structures extend on a strip that inscribes the inner regions of IC 4634 like a thin shell or skin of enhanced \( [\text{O iii}] \) emission. Only the outer envelope (Env) and helical structures (\( H \) and \( Hd \)) are located outside this skin of enhanced \( \text{[O iii]}/\text{H} \alpha \) ratio.

The presence of a skin of enhanced \( \text{[O iii]}/\text{H} \alpha \) ratio is rare among PNe; only in NGC 6543 has a structure of this kind been reported (Balick 2004). In his detailed analysis of narrowband \( HST \) WFPC2 images of NGC 6543, Balick (2004) noted that there is no observational artifact (contamination of \( [\text{N ii}] \) emission in the \( \text{H} \) image or incorrect correction for wavelength-dependent geometric distortions in the camera optics), ionization effect, or local variation of the \( O/\)H abundances or the electronic temperature in NGC 6543 that would be able to produce the observed increase of the \( \text{[O iii]}/\text{H} \alpha \) ratio at the nebular edge. Observational artifacts can also be dismissed as the origin of the observed morphology in the \( \text{[O iii]}/\text{H} \alpha \) ratio map of IC 4634, since the emission in \( [\text{N ii}] \) is much weaker than in \( \text{H} \alpha \), as can local variations of the \( O/\)H abundances, which are rather constant throughout the nebula. Emission from the main nebula scattered in the outer layers of the PN can also be excluded, as the \( \text{[O iii]}/\text{H} \alpha \) ratio in the skin of these layers is significantly different from the ratio value measured in the bright, innermost regions of the nebula. The only plausible cause of the observed enhancement in the \( \text{[O iii]}/\text{H} \alpha \) ratio is a local increase of \( O^{+}/\text{H}^{+} \) or \( T_{e} \).

Balick (2004) concluded that the origin of the skin of enhanced \( \text{[O iii]}/\text{H} \alpha \) ratio in NGC 6543 was uncertain. In IC 4634, this structure is related to the bow shock structures \( A-A', B-B', \) and \( C-C' \), and therefore it can be speculated that it originates in the interaction of fast collimated outflows with the nebular material. The shocks produced by fast collimated outflows would excavate a cavity in the low-density nebular envelope and propagate outward, inducing a marginal increase of the electronic
temperature in a forward shock that would enhance the $[\text{O} \text{iii}]$ in a manner also observed in windblown bubbles around WR stars (Gruendel et al. 2000). A similar origin can be attributed to such structure in NGC 6543, as suggested by the caps of enhanced $[\text{O} \text{iii}]/\text{H} \alpha$ associated with the jetlike features of NGC 6543 (see Fig. 2 of Balick 2004).

### 3.5. The Outer Envelope

The *HST* images of IC 4634 reveal an envelope of faint emission surrounding its central regions that we have labeled "Env" in Figure 1. This envelope has a patchy appearance, with a distinct arc toward the east and individual filamentary (F-F) and arclike (G) features toward the west. Some of these features are best seen in the $[\text{O} \text{iii}]/\text{H} \alpha$ ratio map shown in Figure 1 (bottom right). Overall, the morphology of the envelope can be classified as elliptical, with its major axis along P.A. $\sim 120^\circ$.

Since the envelope is more clearly detected in the $\text{H} \alpha$ and $[\text{O} \text{iii}]$ images than in the $\text{N} \text{ii}$ image, a high excitation is suggested. Its surface brightness is low, up to $\sim 1000$ times lower than that of the inner shell in the $\text{H} \alpha$ line. If we assume the same electron temperature as in the inner shell, its density can be scaled down from that of the inner shell to $\sim 100 \text{ cm}^{-3}$.

Finally, the envelope is detected in the high-dispersion spectra, especially in the echellograms of the $\text{H} \alpha$ line. Its emission shows a broad, unresolved line with a radial velocity similar to the systemic velocity. This structure seems to be an inert, irregularly shaped, low-density outer envelope.

### 3.6. The Outer Helical Structure

The existence of a distant string of faint knots associated with IC 4634 was first reported by Guerrero et al. (2004). This feature, labeled $H$ and $Hd$ in Figure 1 (top right), is shown in greater detail in the deep NOT $\text{H} \alpha+[\text{N} \text{ii}]$ image presented in Figure 9. In this figure, $H$ and $Hd$ are composed of several knots detected from P.A. $\sim -5^\circ$ to $20^\circ$ at angular distances $37^\prime\prime-64^\prime\prime$ from the central star of IC 4634. In the *HST* images, the knots in the structure $H$ are either resolved into compact cores surrounded by clumpy emission or show the appearance of a string of knots. Morphologically, component $H$ forms an arclike string of knots whose orientation is different from that of the major nebular axis, but similar to that of components $B-B^\prime$ and $D-D^\prime$. Component $Hd$ consists of several faint diffuse knots, including a large ($\sim 25^\prime\prime$) corkscrew-shaped structure oriented along the north-south direction. We obtained deep narrowband images to search for a possible southern counterpart of $H$ and $Hd$, but our search yielded negative results.

The $\text{H} \alpha$ and $[\text{N} \text{ii}]$ emission from $H$ and $Hd$ is detected in the high-dispersion spectroscopic observations. The emission lines can be fit with a single Gaussian profile with FWHM of $\sim 25 \text{ km s}^{-1}$ in the $\text{H} \alpha$ line and $\sim 20 \text{ km s}^{-1}$ in the $[\text{N} \text{ii}]$ at $6584 \text{ line}$. The systemic radial velocity derived from these lines is very similar to the systemic radial velocity of the nebula.

### 4. A PRECESSING COLLIMATED OUTFLOW IN IC 4634

#### 4.1. Observational Evidence and Similarities to Herbig-Haro Objects

The morphology of the bow-shaped features $A-A^\prime$, $B-B^\prime$, and $C-C^\prime$ resembles that of Herbig-Haro (HH) jets. These jets are morphologically characterized by chains of aligned knots with bow shock–like appearance and a leading bow shock, the “head” of the jet, where the supersonic flow slams into the surrounding material. Observations of the knots of HH jets have been interpreted by several authors as being the result of time-dependent variations in the velocity of the flow (see, e.g., Raga et al. 1990). Such a jet model with variable ejection velocity has been shown to reproduce the overall morphology and kinematical properties of the high-velocity jets of the proto–planetary nebula Hen 3-1475 (Velázquez et al. 2004). The bow shock structure of $A-A^\prime$, $B-B^\prime$, and $C-C^\prime$ is consistent with those features’ being the result of a jet, ejected with variable velocity, which interacts with the AGB remnant.

The suggestion drawn from the morphology of IC 4634 is reinforced by the kinematics of $A-A^\prime$. Its $\text{H} \alpha$ and $[\text{O} \text{iii}]$ PV diagrams clearly show a wedge-shaped feature analogous to those observed in several HH objects (e.g., Böhm & Solf 1985). A wedge-shaped feature in the PV diagram is expected for a bow shock moving nearly on the plane of the sky, as predicted by the traditional “1.5-dimensional” bow shock model, which is a reasonable approximation to the leading bow shock of an HH jet (Raga & Böhm 1985, 1986; Hartigan et al. 1987). In such a case, the radial velocity dispersion increases suddenly at the stagnation point of the bow shock, producing a line broadening that looks like a horizontal edge in the PV diagram. The amount of broadening of the emission-line profiles can be related to the velocity of the bow shock (Hartigan et al. 1987). In the case of $A-A^\prime$, the observed width of the line would indicate a bow shock velocity of $\sim 100 \text{ km s}^{-1}$. We conclude that the PV diagrams of $A-A^\prime$ are, at least qualitatively, compatible with the predictions of a leading bow shock (i.e., the “head” of a jet) that is nearly on the plane of the sky.

Further support for this scenario is provided by the spectral properties of $A-A^\prime$. The dereddened emission-line ratios in these regions with intense emission in low-ionization lines are reminiscent of shock-excited nebulae such as HH objects. While shocks might be collisionally exciting the low-ionization emission lines of $A-A^\prime$, a detailed comparison of the observed emission-line ratios with spectra predicted by photoionized shock models (e.g., Dopita 1997) is not straightforward, since the bow shocks in IC 4634 are illuminated by the stellar ionizing flux from the...
postshock direction. A more realistic comparison is enabled by the axisymmetric numerical simulations, recently obtained by Riera & Raga (2008) and Raga et al. (2008), of a shocked, dense cloudlet moving away from a source of ionizing photons through a uniform and photoionized environment. These simulations not only produce synthetic spectra that are qualitatively consistent with the spectra of A-A', but also reproduce the ionization stratification of A-A', in which the gas in the downstream region is more highly ionized than the outward-facing edge, and the [O iii] emission shows a larger extension toward the photoionizing source.

It is thus tempting to interpret the point-symmetric morphology of IC 4634 as the result of moderate-velocity jets with a time-dependent ejection velocity. Furthermore, the point-symmetric morphology of IC 4634, which gives the nebula its S-shaped appearance, and the varying sign of the radial velocity are commonly interpreted as being the direct result of a time-dependent direction of ejection of the source. In the next section, we explore in further detail this supposition, which may in general be of interest with regard to other point-symmetric PNe (Cliffe et al. 1995; Lee & Sahai 2003; García-Arredondo & Frank 2004; Velázquez et al. 2004; Soker & Bisker 2006).

4.2. Modeling a Precessing Collimated Outflow in IC 4634

4.2.1. Initial Conditions and Numerical Methods

The morphology and kinematics derived for IC 4634 place important constraints on and provide clues to some of the parameters describing the motion of such a precessing outflow. The bow shock morphology of A-A', and the spatial distribution of the [O iii] and Hα emission preceding the [N ii] emission, reveal shock excitation. The observed radial velocities are low, suggesting that the angle between the precession axis and the plane of the sky, the inclination angle i, is small. We thus assume that the precession axis is on the plane of the sky. Finally, the semimajor axis of the aperture of the precession cone, α, can be derived by measuring the angle subtended by A and B with respect to the central star. This angle is estimated to be ∼11°.

Numerical simulations were carried out with the three-dimensional code YGUAZU-A (Raga et al. 2000, 2002), using a five-level binary adaptive grid. The dimensions of the computational domain were 2.2 × 10^{17} cm in the x- and y-directions, and 4.4 × 10^{17} cm in the z-direction, i.e., 6.3° × 12.7° at a distance of 2.3 kpc, with a maximum resolution of 8.6 × 10^{14} cm, i.e., ∼0.025°. This code integrates the gas-dynamic equations by using the “flux vector splitting” scheme of Van Leer (1982). Together with the gas-dynamic equations, several rate equations for the atomic/ionic species were also integrated. These species are H i, He i, He ii, C i, C ii, C iii, N i, N ii, N iii, O i, O ii, O iii, O iv, S ii, and S iii (see details of the reaction and cooling rates in Raga et al. 2002). These rate equations enable the computation of a nonequilibrium function for the radiative losses. Given a set of initial conditions for the jet and surrounding circumstellar medium (CSM), YGUAZU-A determines the temperature and density distributions at a given time. The temperature and density distributions allowed us to compute the emission-line coefficients of the Hα, [N ii] λ6584, and [O iii] λ5007 emission lines. The intensity of the Hα line is computed considering the contributions from the recombination cascade and from n = 1 → 3 collisional excitations. The intensities of the forbidden lines [N ii] λ6584 and [O iii] λ5007 are calculated by solving five-level atom problems, using the parameters of Mendoza (1983). These intensities can be integrated along the line of sight to produce synthetic emission maps and PV diagrams for a wide slit that completely covers the working surfaces.

A jet of number density n_j is injected into the base of the computational domain (z = 0) at position (1.1 × 10^{17} cm, 1.1 × 10^{17} cm) in the x-y-plane, with a radius and length of 2.6 × 10^{15} and 4.3 × 10^{15} cm, respectively. The jet density is assumed to be 10^4 cm^{-3}. The jet velocity is modeled by the relationship

\[ v_j(t) = v_0 + \Delta v \sin \left(2\pi \frac{t}{\tau_p}\right), \]

where \(v_0\) is the mean velocity, \(\Delta v\) is the amplitude of the velocity variation, \(t\) is the time, and \(\tau_p\) is the period of the velocity variation. The symmetry axis of this jet precesses with period \(\tau_p\).

The surrounding CSM is assumed to be produced by an AGB wind of constant mass-loss rate \(\dot{M}\) and expansion velocity \(v_{AGB}\). The dependence of the density of such a medium on the radial distance to the central star \(r\) is given by

\[ \rho(r) = \rho_0 \left(\frac{r_0}{r}\right)^2, \]

where the density \(\rho_0\) at radius \(r_0\) is determined by the mass-loss rate and expansion velocity of the AGB wind as \(\rho_0 = \dot{M}/(4\pi r_0^2 v_{AGB})\).

In our simulations, the mass-loss rate and expansion velocity of the AGB wind were assumed to be 10^{-6} M_\odot yr^{-1} and 20 km s^{-1}, respectively. The temperature of the CSM was set to 100 K.

4.2.2. Results of Numerical Simulations

Several numerical simulations were carried out varying \(v_j\), \(\Delta v\), \(\tau_p\), and \(\tau_i\) to produce synthetic emission maps and PV diagrams that can be directly compared to the observed images and long-slit echellograms of A-A', B-B', and D-D'. There is a qualitative agreement between the synthetic and observed images and PV diagrams for \(v_j = 300\) km s^{-1}, \(\Delta v = 25\) km s^{-1}, \(\tau_p = 460\) yr, and \(\tau_i = 110\) yr (Figs. 10 and 11). The jet expansion velocity implies a jet mass-loss rate of \(\sim 2 \times 10^{-7} M_\odot\) yr^{-1}.

Figure 10 displays the Hα, [N ii], and [O iii] simulated emission maps obtained for a calculation time of 500 yr. At this time, the jet structure achieves a length of 3.3 × 10^{17} cm, which corresponds to an angular size of 9.8° at a distance of IC 4634 of 2.3 kpc. The upper panels correspond to the y-z projection (i.e., a line of sight along the x-axis), while the bottom panels represent the x-z projection (i.e., a line of sight along the y-axis), which is basically the initial direction along which the jet is emitted. Several working surfaces are observed in these maps at distances of 1.4 × 10^{17}, 2.4 × 10^{17}, and 3.3 × 10^{17} cm, which are produced by the variability of the jet velocity when slow gas is swept up by fast material. The observed morphology and spatial distribution of A-A' and B-B' are more closely reproduced by the y-z projection than by the x-z projection. We note that the spatial separation seen at the head of the A-A' features between the Hα and [O iii] emissions is not reproduced by the synthetic emission maps, because the spatial structure of the region behind the shock, where the [O iii] emission mainly arises, is poorly resolved in our simulations.

Figure 11 displays the Hα, [N ii], and [O iii] simulated PV diagrams obtained at the same calculation time as Figure 10. The centroids of the working surfaces in these PV diagrams do not show the alternate positive and negative velocities observed in A-A' and B-B' exactly, although they display similar sinusoidal variations with respect to the systemic velocity. This indicates that the initial direction along which the jet is emitted is coincident with neither the y-z nor the x-z projection, or that the inclination angle differs from the one that has been assumed. On the
other hand, a close examination of the PV diagrams in Figure 11 reveals a good agreement with the detailed kinematics of the working surfaces: the velocity widths or FWHMs of the synthetic emission lines are comparable to the observed ones, with larger values of the FWHM for the Hα/C11 line; the wedge-shaped tips of the Hα and [O iii] emission-line profiles of A-A0 are also well reproduced.

5. DISCUSSION

5.1. Multiple Shaping Agents in IC 4634

The data presented in the previous sections reaffirm the known complexity of IC 4634. The nebula is composed of a series of morphological components that clearly reveal the action of different shaping agents. Of the prevalent shaping mechanisms in IC 4634, we shall consider the interaction of the current fast stellar wind with the slow AGB wind, the ionizing flux of photons from its central star, and a series of fast collimated outflows. We discuss below the effects that the fast stellar wind and fast collimated outflows have had in the shaping of IC 4634.

IUE observations of the central star of IC 4634 uncovered prominent P Cygni profiles in the C iii, C iv, N v, and O v lines superposed on the stellar continuum. These P Cygni profiles manifest the presence of a fast stellar wind, whose terminal velocity has been derived to be 3500–4000 km s⁻¹ (Hyung et al. 1999). This fast stellar wind has excavated a central cavity within the nebula, compressing the nebular material into a thin shell. This thin shell and the central cavity can be identified with the inner shell IS, while the nebular envelope can be associated with the faint shell OS surrounding this inner shell. In this respect, the double-shell morphology of the inner regions of IC 4634 compares well with other PNe (e.g., NGC 6826).

The bow shock morphology and spatial distribution of A-A′, B-B′, and C-C′ are highly indicative of the interaction of precessing collimated outflows with surrounding material. Indeed, the detailed morphology and kinematics of A-A′ and B-B′ are successfully reproduced, assuming the interaction of a precessing jet with a time-dependent velocity in the range of 300 km s⁻¹ and a precession period ~460 yr. This jet is interacting with material in the outer regions of IC 4634 that forms the envelope, Env, a region of rough elliptical symmetry that may represent an episode of major mass loss prior to the one that formed the inner regions of IC 4634. In their interaction, the collimated outflows generate bow shock structures and drive a forward shock that produces a high-excitation skin.

Two of the new nebular components revealed in this work are the outermost features H and Hd. The location of H and Hd with respect to IC 4634 and their similar radial velocities make it unlikely that these components are unrelated to the nebula. The morphology of the H feature, which is composed of a series of knots distributed along an arclike structure, can be interpreted as a loop on the surface of an imaginary cone whose vertex is...
coincident with the central star of IC 4634. Therefore, $H$ and $Hd$ may correspond to an ancient precessing ejection. It is worth emphasizing that the precession axis of this ancient ejection would be almost orthogonal to the axis of the precessing ejection that has been considered for $A'A'$ and $B'B'$. There are, thus, clear signs that the innermost shell of IC 4634, IS, and the envelope, Env, were formed by the action of the current fast stellar wind on material associated with episodes of mildly asymmetric mass loss produced during the late AGB, while the bow shock structures $A'A'$, $B'B'$, and $C'C'$, and the arclike features $H$ and $Hd$, were produced by the action of fast, precessing collimated outflows. These collimated outflows may also have played a role in the shaping of the innermost regions of IC 4634, although the evidence is not overwhelming. The inner shell of IC 4634, IS, is elongated and shows morphological and kinematical signs of blowout along its tips. While the origin of the asymmetry of IS can be attributed to a density enhancement in the equator of the nebular envelope, as suggested by the bright emission in the surrounding material along the minor axis in the Hα and [O III] lines, it is worthwhile to note that the orientation and inclination of the collimated outflows associated with $A'A'$ are coincident with those of the blowout along the tips of the inner shell. Therefore, it is possible that the collimated outflows responsible for $A'A'$ may have been involved in the emergence of the blowout structures of IS and in the development of the axisymmetry of this shell. This may also be the case for the inner shells of several PNe with collimated outflows (e.g., NGC 6210 and NGC 6884) that also show the mild point symmetry exhibited by the inner shell of IC 4634.

Similarly, the origin of the $D-D'$ features may be associated with the action of collimated outflows. The kinematics and morphology of $D-D'$ are very similar to those of the low-ionization polar caps described in NGC 6543 (Miranda & Solf 1992; Balick 2004), although these structures may have different inclinations. A thorough discussion of the possible origins of knots and low-ionization structures in PNe is provided by O'Dell et al. (2002). As in NGC 6543, the $D-D'$ arcs of IC 4634 can be interpreted as intrusions of low-ionization, high-density knots that are expanding with the shell that surrounds its inner shell (Balick & Hajian 2004). These features may represent the relic of the interaction of a collimated outflow with the nebular envelope. On the other hand, $Dm-Dm'$, which have higher excitation than $D-D'$, and which are separated from these in the velocity space, can be related to the density enhancement around the equatorial region of IS.

5.2. Bow Shocks in Planetary Nebulae

PNe display a large variety of low-ionization structures, of which fast collimated outflows deserve special attention because of their outstanding kinematical properties (e.g., Gonçalves et al. 2001). The origin and nature of the fast collimated outflows seen in PNe has been disputed, but the morphological, kinematical, and physical properties of some of them seem to be suggestive of high-density bullets moving supersonically through the nebular material (Balick et al. 1994). If this were the case, the interaction of the PN fast collimated outflows with the nebular material should lead to the formation of bow shocks whose morphologies would share some similarities with those of HH objects. Bow shocks would then be expected to be common among PNe with fast collimated outflows; the number of bow shocks identified in PNe, however, is small. In IC 4634, we find one of the rare cases of bow shocks in PNe. The detailed morphology and kinematics of the bow shock structures $A-A'$ and $B-B'$ of IC 4634 can be unambiguously ascribed to a precessing fast collimated outflow, and the morphology and ionization of the bow shock structures $C-C'$ are reminiscent of the interaction of a fast, dense bullet with the nebular material. In view of these findings, it is worthwhile to revisit other cases of bow shocks in PNe.

So far, the best-studied case of a bow shock in a PN is that of IC 4593 (Corradi et al. 1997). In this nebula, we find several systems of knots and inward-facing tails that have been interpreted as multiple collimated outflows propagating along different directions. These knots are preceded by outward-facing caps with bow shock morphologies. The bow shock structures in IC 4593 share many similarities with those of IC 4634. Both have low radial velocities, show a decrease in the observed radial velocity and a broadening of the emission profile, and display caps of enhanced [O III] emission, as expected in bow shock models. All these properties suggest the motion of medium velocity jets near the plane of the sky that are interacting with the surrounding material.

The ansae of NGC 7009 are another promising example of fast, dense bullets ramming through the outer shells of the nebula, although this interpretation has been questioned, as the ionization state of the gas declines at the head of the bow shock (Balick et al. 1998), while the opposite is expected in bow shocks (Hartigan et al. 1987). However, the observed ionization gradient can be reproduced by numerical simulations of a shocked cloudlet moving away from the central star if the stellar ionizing photon flux, which modifies the ionization and excitation structure of the shock, is included (Riera & Raga 2008; Raga et al. 2008). In their study of IC 4593 bow shocks, Corradi et al. (1997) noted that the ionizing flux from the central star can play a predominant role in the ionization stratification of bow shocks in PNe. At any rate, an examination of a deep HST WIPPC2 [O III]/Hα ratio map of NGC 7009 reveals that the ansae of NGC 7009 are preceded by caps of enhanced [O III], as expected in bow shocks (Medina et al. 2008; M. A. Guerrero et al. 2008, in preparation).

Besides IC 4593, IC 4634, and NGC 7009, there are very few other cases of bow shocks associated with PNe. The [O III]/Hα ratio image of NGC 6543 (Balick 2004) shows a bow shock structure enveloping the collimated outflows along the polar directions of this nebula (Miranda & Solf 1992), although this structure is not discussed in detail. A bow shock structure has also been described in NGC 6572, although the limited spatial resolution of ground-based images does not allow the authors to study the ionization stratification at the bow shock (Miranda et al. 1999b). A comprehensive investigation of the occurrence of bow shocks associated with the expansion of fast collimated outflows or bullets in PNe is in progress (M. A. Guerrero et al. 2008, in preparation).

6. SUMMARY

Our spatio-kinematical study of IC 4634 has revealed new structural components in this nebula, including what seems to be the relic of ancient precessing collimated ejections, a triple-shell morphology, and a thin skin of enhanced [O III]/Hα, which envelops the nebula and the bow shock structures at the tip of the collimated outflows. Furthermore, the HST images and ground-based echelle spectroscopy provide a detailed view of the physical structure of the bow shock associated with a collimated outflow in a PN. Their morphology and kinematics have been successfully modeled using hydrodynamical simulations in which a precessing fast collimated outflow interacts with nebular material.

IC 4634 seems to have experienced a series of mildly asymmetric mass-loss episodes that have removed the stellar envelope,
yielding to the current fast stellar wind. These periods of mass loss are interspersed with two episodic ejections of collimated outflows that have interacted with the nebular material, which has had important consequences in the shaping of IC 4634. The most recent episode of ejection of collimated outflows is directly responsible for the formation of the bow shock structures $A-A'$, $B-B'$, and $C-C'$ within the envelope, and has played a significant role in the asymmetry and orientation of the inner shell. The probable interaction of this collimated outflow with circumstellar material might be linked to the formation of $D-D'$. Finally, the oldest episode of ejection of collimated outflows caused the formation of $H$ and $Hd$ in the outermost regions. The two ejections of collimated outflows took place at different times during the PN formation. The large misalignment between the ejection axes of the collimated outflows, which gave rise to $A-A'$, $B-B'$, and $C-C'$ on the one hand, and $H$ and $Hd$ on the other, implies that the collimating source experienced important changes between the ejections.

The data presented here were taken using ALFOSC, which is owned by the Instituto de Astrofísica de Andalucía (IAA) and operated at the Nordic Optical Telescope under agreement between the IAA and the NBIfAFG of the Astronomical Observatory of Copenhagen.

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