Double Shells of the Planetary Nebula NGC 7009 Minor Axis

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Abstract

We analyzed the minor-axis spectra of the elliptical planetary nebula (PN) NGC 7009 observed with Keck HIRES with a 0′′862 × 10″ slit placed at about 7″5 and 10″ away from the center and a 0′′862 × 14″ slit at the center. The mean densities derived from the integrated [S II] 6716/6731 A fluxes along the Keck HIRES slit length indicate a density range of 103.3−103.4 cm−3, while the local densities derived from the slit spectral images show a large local density variation of about 103.8−103.6 cm−3: local densities vary more substantially than values integrated over the line of sight. The expansion rates of the main and outer shells obtained by [S II] are about 21.7 and 30.0 km s−1, respectively. The kinematic results of the [S II] spectral lines correspond to the outermost regions of the two shells and are not representative of the whole PN but are closely related to the other emission lines observed in the shell gas. We conclude that the density contrast leads to the formation of the inner shell, while the change in ionization state leads to the formation of the outer shell. We suggest that the inner main and outer shells result from two successive major ejections. The physical conditions of the central star must have been different when these shells first formed.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Planetary nebulae (1249); High resolution spectroscopy (2096)

1. Introduction

Planetary nebulae (PNe) evolved from stars of low/intermediate mass of 0.8–8 Msun reach the final stage of their life after experiencing mass loss during thermal pulses at their asymptotic giant branch (AGB) stage. During a short life span of thousands of years, the central star of the PN (CSPN) emits UV photons, which ionize the surrounding shell gas, expanding at a velocity of 20–30 km s−1. The interacting winds between the hot CSPN and gas shells may play an important role in the formation of PNe (Kwok et al. 1978). The ionized shell gas produces various emission lines, such as the recombination lines of H and He, and the forbidden lines of heavy elements such as N and O. With high-dispersion spectra, one can obtain information regarding the kinematics and geometrical structure of the PN shell and derive chemical abundances.

NGC 7009 is a PN at high Galactic latitude (b = −34°2.5) whose interstellar extinction at Hβ is very low, C = log I(Hβ)/F(Hβ) = 0.08 dex (Hyung & Aller 1995a), where I(Hβ) and F(Hβ) are the intrinsic and observed Hβ fluxes, respectively. The excitation class of the spectrum obtained at the end of the major axis is 5.5, defined by the ratio of [O III]/He II to [O III]/Hβ (Aller 1956). The effective temperature (Teff) of the CSPN is about 82,000 K (Kingsburgh & Barlow 1994). Its distance is known to be around 1.2 kpc (1.2 kpc in O’Dell 1963 and Sabbadin et al. 2004, 2 kpc in Kingsburgh & Barlow 1994, and 1.15 kpc in Kimeswenger & Barría 2018; Gaia).

The derived abundances with the help of photoionization (P-I) codes such as NEBULA by Hyung (1994) or CLOUDY by Ferland et al. (2017) show that NGC 7009 is an O-rich object with an O/C > 1 (Hyung & Aller 1995a, 1995b). Although the derived abundances indicate NGC 7009 is a classic Galactic PN, specific lines such as [N II] and He II show unusually strong intensities that could not be accommodated by a typical ionization stratification effect (Hyung & Aller 1995b; Gonçalves et al. 2003).

NGC 7009 is morphologically classified as an early middle or middle elliptical PN, with a fast isotropic stellar wind in the inner part, surrounded by an inner halo inside the main shell (Balick et al. 1987). The compact and bright nebula is suitable for investigating details of substructures related to its kinematics or evolutionary status. High-dispersion long-slit spectrophotometric observational data of the bright rims, knots, and halos will allow us to define better the kinematic structures of density and temperature, involving the ionization or possible shock in the shells and the outer halo zone (Reay & Atherton 1985; Balick 1987; Balick et al. 1987; Meléndez 1997). Lame & Pogge (1996) derived the electron density map for the whole NGC 7009 nebula, which indicates Ne > 8000 cm−3 in the central region.

Abundance mismatches derived from recombination and forbidden lines present in some PNe were hypothesized to arise partly from temperature fluctuations (Peimbert 1967). Rubin et al. (2002) conducted Hubble Space Telescope (HST) WF/PC2 imaging and STIS long-slit spectral studies for NGC 7009 and they found a rather uniform Tc map within the range of 9000–11,000 K across the nebula with a very low fractional mean-square r2 defined by Peimbert (1967).

Recently, Walsh et al. (2016, 2018) performed similar but more advanced studies with the MUSE integral field spectrograph on the ESO’s Very Large Telescope. From various available emission lines from neutral to the highest ionization (He II and [Mn VI]), they presented the entire surface maps of electron temperature (and r) and density, which were averaged across the line of sight. Using collisional deexcitations of the [S II] 1D1/2,5/2 levels, they derived density maps showing a wide density range of Ne ≈ 3000–8000 cm−3 in the inner bright zone.

Long-slit observations provide information for large spaces from a small number of lines with a limited wavelength range.
Table 1: Keck HIRES Observation

| Slit Center Position | Date (UT) | Exp. (minutes) | Slit Setup (Length) | Slit Center Distance |
|----------------------|-----------|----------------|---------------------|---------------------|
| center               | 1998.08.15| 2              | s1 (14")           | ...                 |
| S-SE                 | 1998.08.14| 25             | s2 (10")           | ~10"                |
| N-NW                 | 1998.08.14| 3              | s2                 | ~7.5                |

Note. Two slit lengths, 14" (s1) and 10" (s2), with the same slit width were adopted. Column (5) indicates the distance of the slit center from the central position. See Figure 1 for the position angles of the slit length direction adopted along the minor axis (PA = +347º).

Echelle spectral observations, such as those of the Hamilton Echelle Spectrograph (HES) at Lick Observatory, have a high-dispersion ability to separate closely spaced lines for many lines. However, the HES provides no spatial information. The Keck High-resolution Echelle Spectrograph (HIRES) has the advantage of long-slit spatial dispersion and high echelle dispersion capabilities. We analyze 2D [S II] 6716.4 and 6730.8 Å spectral images secured with Keck HIRES along the minor axis of NGC 7009. The collisional excitation of singly ionized sulfur, or [S II], has relevance to the study of the Sun, Jupiter’s Io in the solar system (Hall et al. 1994), symbiotic stars (Schmid & Schild 1990), nebulae (Osterbrock et al. 1992), and active galactic nuclei (Osterbrook 1999). Keenan et al. (1996) investigated [S II] transitions to the ground state from two separate metastable states, namely via the deexcitation of the abovementioned (1) 2D → S (6716 and 6731 Å) and (2) 3P → S (4069 and 4076 Å) transitions. They showed that both are sensitive to both electron temperatures and densities up to log N_e = 5 dex cm⁻³. When calculating the line strengths of [S II] 6716 and 6731 Å, we use the 2017 release of the Cloudy code (subversion 17.02) (Ferland et al. 2017).

Section 2 describes observations of the position–velocity (P-V) slit spectral images by Keck HIRES and the data reduction. In Section 3, we derive P-V maps of the density distribution for the innermost bright main and outer shells along the minor axis. We update the radial variation of the expansion velocities of the two shells. In Section 4, we give conclusions.

2. Observations and Data Reduction
The minor axis of NGC 7009 was observed with Keck HIRES on 1998 August 14–15 (UT) by Hyung & Aller. The seeing was slightly less than 1"0 in observation. Several different HIRES slit settings were used because the bright nebular rim size is about 28" × 30" and the slit length of HIRES is smaller than the nebular rim. HIRES has a separation of 8"–43" between the two adjacent echelle orders, which enabled us to obtain spatial information along the slit length direction. Table 1 lists the employed slit information. The [S II] spectral images were secured with two slit (length × width) sets: (a) s1: 14" × 0"862 (6309–8530 Å); (b) s2: 10" × 0"862 (5130–7475 Å). The slit width corresponds to a wavelength dispersion power of R = λ/Δλ = 45,200 (~3 pixels).

Figure 1 shows the nebular image from HST WFPC2 with the F658N filter (PI: Balick; Prop-ID: 6117, NASA/ESA), with a schematic diagram of the employed HIRES slit directions and positions over the nebular image: the S-SE, center, and N-NW pointings along the minor axis (PA = +347º or −13º). Here, we use a nonstandard PA value to indicate the current image is an upside-down version of the standard 167º case. The 2 minute exposure with the 14" slit was done at the CSPN’s position, while 3, 25, and 30 minute exposures with the 10" slit were carried out to cover two bright rims along the minor axis. Here, the locations of the S-SE and N-NW slit centers were at 10" and ~7.5" from the CSPN, respectively. A standard star 58 Aql suitable for the red wavelength region was observed for flux calibration.

We used a 2048 × 4096 pixel CCD in the observation, whose 2048 pixels correspond to the spatial direction (i.e., the slit length). The observed spectral data were reduced with the IRAF5 reduction package. The IRAF long-slit standard data reduction procedure, noao.twodspec, was employed to find the spectral image, keeping the spatial information: (a) zero-intensity-level correction to all frames including bias, flat-lamp, and object correction, and Th–Ar comparison frames using the overscan region of each frame and the mean bias frames; (b) cosmic-ray removal; (c) flat-fielding; (d) a 2D P-V spectrum extraction; (e) wavelength calibration keeping the spatial information; and (f) flux calibration using 58 Aql. We derived a (heliocentric) radial velocity of −48.91 km s⁻¹ from the strong lines (i.e., F(λ) > 1.0 on the scale of F(Hβ) = 100) from the IRAF 1D standard data reduction procedure, noao.echelle, for the same Keck HIRES data. Our value is close to the radial velocity of ~49 km s⁻¹ derived through the HES data at Lick Observatory (Hyung & Aller 1995a). The derived radial velocity would allow us to convert the observed wavelengths (λ₀) of the two spectra to the ones at the proper coordinate system of the PN, λₚ = λ₀ + Δλ, where Δλ = +[(48.91/c) × λ₀] (λ₀ is the theoretical wavelength, 6716.47 Å and 6730.85 Å; Moore 1972, 1993). The redefined wavelengths would become the kinematic reference point.

Several painstaking steps are required to obtain the electron density from the wavelength-calibrated flux via IRAF (see Figures 4 and 5). We converted the wavelength to kilometers per second for the x-axis to avoid possible errors during the reduction process (e.g., the superposition or interpolation of an [S II] 6716 line profile and an [S II] 6731 one). Then, we expect the observed line centers of the two theoretical [S II] 6716.47 Å and [S II] 6730.85 Å lines to correspond to Vₑ = 0 km s⁻¹.

After obtaining the continuum-subtracted flux values on a 2D position–wavelength plane with IRAF, we further analyzed them on a 2D P-V plane with reduction algorithms written in Starlink/Dipso5 and IDL.6 Finally, we derived density distribution P-V maps from the [S II] 6716, 6731 P-V diagrams.

3. The P-V Density Distribution Map
The 3D structure models by Sabbadin et al. (2004) and Steffen et al. (2009) showed that the main shell of NGC 7009 is a density-contrast prolate ellipsoidal shell. The 2D H I or Hα

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4 IRAF is distributed by the National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.

5 http://starlink.eao.hawaii.edu/starlink

6 http://idlslgroup.com
spectral images will display the characteristics of the overall kinematics of the PN. Meanwhile, the 2D [S II] spectral images would give us information on the [S II] subshell that H I does not reveal: an H I line broadening is about six times larger than an [S II] line for the same electron temperature.

3.1. Two Main Shells

3.1.1. The H α P-V Map

Sabbadin et al. (2004) presented the [N II], H α, [O III], and He II narrow filter slit images for 12 PAs and constructed a 3D structure with the help of P-I models. In addition, they presented the radial variation of ionization structures (He II, He II, O II, O I, N II, Ne, S II, S III, Ar III, and Ar IV, relative to O III) across the minor axis (PA = 169°) and the major axis (PA = 77°). The ionization regions of S II and N II extend farther to the N-NW than to the S-SE direction. Unlike those of the other six ions, the intensities of S II and N II relative to H α are higher in the outer part, perhaps due to the hardening and dilution of the UV radiation field from the central star in the outer region due to its distance from the central star.

The spectral images by Sabbadin et al. (2004) show that the outer [N II] shell is a structure of a complex, broad shell filled with material that appears to be detached from the bright main shell, while the H I and [O III] images look like a part tied to the inner main shell (see their Figures 2 and 3). Meanwhile, the main shell shows a possible thin triaxial ellipsoid broken along the major axis (projected in PA = 77°). This is not a typical case for the equatorial region slit spectra of a prolate shell, implying a possibility that the two shells were formed by different mechanisms. The four [N II], H I, [O III], and He II P-V spectral images for the minor axis by Sabbadin et al. (2004) show that the velocity structure of the bright inner rim and the matter outside the rim are different. The integrated image in Figure 1 also clearly shows that the physical structure is similar to what they found. The radial distribution of the main shell shows a sharp, bell-shaped profile with an N_e ([S II]) of up to 4000 (±500) cm⁻³ along the major axis and 7000 (±500) cm⁻³ along the minor axis (Sabbadin et al. 2004). Our present study on HIRES 2D spectral images refines this earlier extensive work on the minor axis by Sabbadin et al. (2004). The two velocity ellipses show misalignment. We tried to derive expansion velocities and densities more accurately, taking into account the orientation of the shells based on the [S II] spectral images secured along the minor axis.

Figures 2(a)–(c) show two different images: the green–blue false colors on the left are slit images obtained during observation, while the white–blue false colors on the right are images of the H α spectrum obtained by analyzing the light entering the slit entrance. The oval 2D shape of the images is artificial in that the x-axis is the wavelength component in units of angstroms, and the y-axis is the spatial component in arcseconds. The box size in Figure 2(a) is 14″ × 3 Å. Note that the top is oriented to the S-SE, and the bottom is oriented to the N-NW.

The H α spectral image along the minor axis in Figure 2(a) generally shows a bilaterally symmetric and roughly point-symmetric elliptical rim. Still, the red-side rim appears to be broken, implying a deviation from the toroidal symmetric structure. Figuring out the physical conditions or identifying unique substructures could help allow us to understand the history of PN formation or evolution. The H α spectral images help us to know the overall structure of the nebula or where most of the mass is.

The S-SE and N-NW spectral images in Figure 2 clearly show the middle zone located outside the bright main shell. Hyung et al. (2014) performed a somewhat preliminary analysis of Keck spectral images to find radial velocity variations of the inner bright shell (main shell) and the faint outer shell. Their analysis indicates the Hubble-type expansion of two shells with a velocity jump or a nonzero starting velocity near the inner shells. We will update these results in this study. Figures 2(b) and (c) show a slight increase in the H α emission at the extremes of the outer shell. The H α width due to the thermal line broadening using the same T_σ0 = 10,000 K would be much broader than that of [S II], i.e., 21.6 km s⁻¹ versus 3.82 km s⁻¹, so the H α emission line is not suitable for investigating the boundary structure of the shells. Note that the wavelength dispersion width (3 pixels due to the employed slit width) is 6.7 km s⁻¹.
The appearance of a double-shell structure (or rim) might consist of (1) the inner relatively high-density main shell and (2) the bright outer region of [N II] or [S II] emission by increasing the increased fractional ionization in this region due to the diluted UV radiation. As a result, a double-shell shape might appear. However, looking at the radial variation of logarithmic [O III] flux along the minor axis (PA = 169°) in Figure 7 of Sabbadin et al. (2004), we can see a continuous flux distribution between the two shells. Still, two flux peaks appear at about the same position as the other low-excitation lines, and the double shells are also well defined in this medium-excitation [O III] line image: the relative peak fluxes of the main shell, intermediate zone, and outer shell are approximately 1, 0.5, and 0.8, respectively.

The multiple shells described in this study and in Sabbadin et al. (2004) could be part of a single structure, as the surface brightness profile, e.g., from the HST, shows an ellipsoid-like structure. The mechanism of the main shell and the outer shell having different shapes will require an ad hoc modification of the radial variation of the densities and the physical conditions for fractional ionization to produce the observed double-shell feature.

3.1.2. Densities Averaged over the Line of Sight

Walsh et al. (2018) derived density maps over the whole nebula image, corresponding to the integrated fractional volume across the line of sight, based on the [S II] 6716/6731 Å and [Cl III] 5518/5538 Å line ratios. The former derived density map shows a wide density range of \( N_e \sim 3000–8000 \text{ cm}^{-3} \) in the inner bright zone, especially a high density in the bright rims (the main shell) of the minor axis. Meanwhile, the latter map indicates a low-density range of \( N_e \sim 3000–5500 \text{ cm}^{-3} \) (see their Figure 7). The Paschen lines are in a part of the spectrum that is difficult to measure carefully due to atmospheric emission and absorption. The densities derived by the H I Paschen lines (P15–P26) also suggest the presence of much higher densities \( \sim 15,000–20,000 \text{ cm}^{-3} \) in the minor-axis zone (see their Figure 11). These density maps, however, represent the average value of the pencil-beam cross-section and the actual density consists of higher and lower density values. Their [S II], [Cl III], and H I density maps generally show similar morphology and structures, but amplitudes and absolute values vary depending on the ion used, perhaps due to the atomic data.

In a narrowband-filter [S II] 6716/6731 Å Fabry–Perot interferometry study, Lame & Pogge (1996) identified an elliptical high-density structure with a maximum density of 10,000 \text{ cm}^{-3} with its major axis deviating by 50° from the major axis of the NGC 7009 rim. Their results mostly agree with Walsh et al. (2018). The densities of the minor axis appear to be higher than those of the major axis.

In an analysis of NGC 7009 major-axis HST data, Phillips et al. (2010) found the [S II] 6716/6731 ratios of regions corresponding to 0″–5″ and 5″–15″ to be 0.59–0.72 and 0.5–0.65, respectively, corresponding to density ranges of \( N_e \sim 10^{3.2-3.5} \) and \( 10^{3.5-3.8} \). In the outer 10″–25″ region, the density ranges are comprehensive, \( N_e \sim 10^{2.7-3.2} \) corresponding to ratios of 0.37–0.95. Hyung & Aller (1995b) gave density values (log \( N_e = 3.55–4.3 \text{ cm}^{-3} \)) derived from the Lick HES lines for the minor-axis bright rim at 5″–6″ from the center assuming \( T_e = 10,000 \text{ K} \) (see their Figure 1).

3.1.3. Density from 2D [S II] Maps

Figure 3 shows the density diagnostic diagram of electron densities versus [S II] 6716/6731 Å ratios, produced by Cloudy P-I calculations assuming \( T_e = 10,000 \text{ K} \) with Cloudy 17.02 (Irinia & Fischer 2005; Tayal & Zatsarinny 2010). For spectral image analysis, we used this diagnostic diagram.

Figure 4 shows the [S II] 6716 and [S II] 6731 lines in one echelle order. We checked the line ratio from the integrated
Figure 3. Density vs. [S II] 6716/6731 Å ratio. The P-I model by Ferland et al. (2017) is indicated with open circles, assuming $T_e = 10,000$ K. See the text.

Figure 4. The spectral scan, showing the [S II] 6716 Å and [S II] 6731 Å lines in one echelle order. The flux on the y-axis is in units of erg cm$^{-2}$ s$^{-1}$ (e.g., 2.0×10$^{-15}$). The spectral scan is from one spatial component or a single row of the CCD, corresponding to the 4″ N-NW position from the center (see Figure 2(a)). Each pixel corresponds to $Δλ = λ/(5R)$. The continuum level has been adjusted. See the text.

[S II] line fluxes at a specific spatial position from the Keck HIRES data as depicted in Figure 4, which shows that the ratio does not differ from the Lick HES [S II] line ratio.

Figure 5 shows the two flux profiles of [S II] 6716 Å and [S II] 6731 Å. These two flux profiles are replotted to overlap with each other with respect to the pixel numbers in Figure 5. To estimate fluxes for [S II] 6716 Å and [S II] 6731 Å at each pixel, we had to remove the continuum flux. After determining the continuum level with a first-order spline function in the raw spectral scan avoiding the emission [S II] line spectrum itself, we subtracted the continuum from the raw line spectral scans (Figure 4). As in Figure 4, the spectral noise in one spectral scan is more or less constant in all wavelength ranges, while the flux level of [S II] varies according to the shape of the line profile. The value of the signal-to-noise ratio (S/N) becomes worse at a weak-flux point.

We also corrected for interstellar extinction with an extinction coefficient of $C = 0.08$. Two clearly well-defined rims of the main shell and the other, outer shell are seen in both lines. Figure 5 shows two overlapping spectra extracted from a fixed spatial component as in Figure 4. The x-axis in Figure 5 is the pixel corresponding to the wavelength. One must correct the wavelength dispersion first to calculate the line intensity ratio. However, plotting Figure 5 as flux versus velocity would simplify the necessary task.

The obtained P-V density map should match the others in the overlapping zone. The wavelength identification was done with the IRAF 2D long-slit data reduction procedure (n duo. twodspec) and the whole 2D spectral image had to be aligned. As with all other echelle orders, the HIRES spectral scans are slightly curved when recorded on a CCD of the spectrometer. Hence, one needs to do an IRAF reduction procedure that rotates the 2D raw image to align the 2D image parallel to the horizontal axis. These processes may lead to errors in wavelength identification. However, the error is not significant for our [S II] spectral scan echelle order. Note that there is an overlapping zone between the two different slit spectral images.

The measured S/N of the four peaks of the line profiles in Figure 5 are 32.5 and 27.7 (main rings) and 5.26 and 10.4 (outer rings), which correspond to errors of 3.1% and 3.6% (main rings) and 17.8% and 9.6% (outer rings), respectively. The signal is proportional to the flux intensity, but the noise in the continuum near the line remains about the same in one spectral order: the S/N $\sim \sqrt{t} \times$ flux for an exposure time $t$. The S/N of the spectral line segment of a roughly Gaussian line profile is higher at the center of the line profile (or ring) but becomes lower at the edge. Weak [S II] flux regions are low-S/N regions, which are marked in black in Figure 6. There are zones with a ratio of [S II] 6716 Å/[S II] 6731 Å below 0.45, which corresponds to a high electron density of $N_e \simeq 4.5$ dex (see Figure 3).

Figure 6 shows the [S II] 6731 Å 2D spectral images in logarithmic flux scale and P-V density distribution contour maps at the three slit positions—the S-SE rim, the CSPN, and the N-NW rim—secured with the slit entrances in Figure 2 along the minor axis (PA = +347°). Note that the present Keck 2D spectral images correspond to a PA = +169° [N II] image by Sabbadin et al. (2004; see their Figure 3), but with the top and bottom of the images reversed. The logarithmic-scale 6731 Å spectral images appear to be simple in shape, but the P-V density maps look very fuzzy and messy around the low-S/N perimeter. The high-S/N images in Figure 7 show two
main shell structures well. However, the 25 and 30 minute exposure density images in Figure 7 seem to obscure detailed information about the main shell boundary. The discordance may reflect the difficulty of getting an appropriate result due to the seeing conditions in the low-S/N region and the flux minimum cut levels. Hence we prefer Figure 6. There is some overlap between the spectral image secured with the slit placed at the CSPN in Figure 6(b) and those of Figures 6(a) and (c).

Figure 6 shows the P-V density maps of short-time exposures of 3, 2, and 3 minutes, while Figure 7 shows maps from long-time exposures of 25 and 30 minutes. In Figures 6 and 7, we set the range of the color bar legend to $\log N_e = 2-5$ dex. The densities are mainly in the range of $\log N_e = 2.8-4.6$ dex, except in Figure 6(f), which shows one region of 4.7 dex. However, Figure 7(b) shows that the densities of the same area are 4.6 dex, whose difference is within the marginal error of 0.2 dex. Taking all the circumstances into account, we conclude that the maximum density is about 4.6 dex.

There is a notable difference in density structure between Figures 6(e) and (f), i.e., the lower part of the two shells. It is unavoidable to see relatively large noise in the short-exposure 2D images since we subtracted the almost-linear continuum level (i.e., the first-order spline). In other words, we only...
corrected the continuum level, not the noise’s details. The shorter the exposure time, the greater the noise level of the obtained image. From many trials and errors to avoid poor-S/N zones in the maps, we set the minimum flux level at the 1.5% level of the maximum flux for the S-SE maps in Figures 6(d) and 7(a), at a slightly higher 2% level for the N-NW maps in Figures 6(f) and 7(b), and at a 4% level for the center map in Figure 6(e). The lower minimum flux level at the 1.5% level in Figure 6(d) seems to bring out some interesting features between the two shells more clearly, which are not discussed in this study. Different relative flux limits mean a more or less constant absolute flux limit for avoiding low-S/N zones in the short spectra.

Table 2 lists the measured (mean) S/N values for the peaks of the [S II] 6716 and [S II] 6731 fluxes involving the density derivation. The designations (d)–(f) in Column (1) indicate the panels in Figure 6, and the arcsecond values designate the distance from the center. Columns (2)–(5) give the S/N of the stronger [S II] line profiles of the main shell and the outer shell along the minor axis at selected spatial positions. We distinguish between the blue and red components of the main and outer rings. The presence of main and outer shells is evident in the spectral images. We only provide the S/N values for the most substantial peak of the shells whenever their presence is apparent from the images and the spectra, as seen in Figure 4. Note that the S/N of the long exposure is much higher than that of the short exposures at 201 (25 minutes) (not shown) versus 66.5 (3 minutes) at the same −4″ position of the receding main shell. The measurement errors of the fluxes are similarly large (5%–10%) for the short exposures of 2–3 minutes in Figures 6(d)–(f) and small (1%–5%) for the long exposures of 25 and 30 minutes in Figures 7(a) and (b). The difference between the deep-exposure and short-exposure images is mainly in the peripheral boundary or the weak-intensity region between the two main shells.

Figure 8 shows a plot of the mean density as a function of position along the slit length for the central slit position. Note that the slit size is 14″ while the number of data points is 38. Hence, we chose the slit position from every other data point to mimic the seeing slit size, e.g., (2), (4), ..., (36). The derived

![Figure 7. Keck HIRES [S II] 6731 Å spectral image and derived densities: (a) 25 minute and (b) 30 minute exposures. The minimum flux cuts with respect to the maximum fluxes are 1.5% for (a) and 2% for (b). See Figure 6 caption and the text.](image)

### Table 2

| Position | Main (Blue) | Main (Red) | Outer (Blue) | Outer (Red) |
|----------|-------------|------------|--------------|-------------|
|          | S/N | S/N | S/N | S/N |
| (d)      |     |     |     |     |
| 10″      | ... | ... | 19.7 | 20.4 |
| 8″       | ... | ... | 16.5 | 12.5 |
| 6″       | 10.1 | 16.0 | 7.75 | 5.1 |
| 4″       | 23.3 | 36.6 | 18.6 | ... |
| (e)      |     |     |     |     |
| 6″       | 18.5 | 16.7 | 3.31 | 57.1 |
| 4″       | 32.5 | 27.7 | 5.62 | 10.4 |
| 2″       | 22.2 | 21.6 | 9.55 | ... |
| −2″      | 17.4 | 56.8 | 15.3 | ... |
| (f)      |     |     |     |     |
| −4″      | 33.8 | 66.5 | 22.3 | ... |
| −6″      | 15.8 | 96.3 | 17.4 | ... |
| −8″      | ... | ... | 15.7 | 18.0 |
| −10″     | ... | ... | ... | 28.0 |

**Note.** Column (1): Offset y position. See Figure 6.

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values at the boundaries were ignored due to the uncertainty. The Keck observations show the density structure along the line of sight, resolved in velocity. The P-V density maps in Figure 6 show high local densities and considerable variations along the line of sight. Such a local density variation is only available with observations that resolve the structure along the line of sight in velocity.

The densities from the integrated slit cross section indicate a much narrower density range of 3.69–4.09 (±0.14) cm⁻³. These values are similar to the other densities integrated over the line of sight in Section 3.1.2. The error bars indicate the density disagreement between the value at each chosen slit position and the three-point smoothing mean value, e.g., a smoothing mean value for slit position 2 was obtained by averaging the three values for positions 1, 2, and 3. The actual errors might be smaller since the integrated fluxes are larger than the local fluxes (see the S/N obtained from each point in Table 2). A comparison of Figures 6(e) and 8 seems to show that the high-dispersion slit spectral images would be an excellent tool for finding locally varying densities along the line of sight.

The range of local densities of the main and outer shells in Figure 6 is log N_e ≈ 2.8–4.6 dex [cm⁻³] (see also Figure 7). Table 3 lists the local density ranges of the two main shells. The last three lines of Table 3 give the density derived from the integrated flux in Figure 4 and the Lick HES data (Hyung & Aller 1995a, 1995b) using the Cloudy P-I code result. The [S II] 6716/6731 Å line ratios are given in brackets, indicating presumably high electron densities in the [S II] emission zones.

The S-SE rim (or shell) of Figure 6(d) and the N-NW rim of Figure 6(f) indicate the densities in both the main and outer shells, which are as high as log N_e = 4.6 dex (40,000 cm⁻³). The inner main shell consists of a complex substructure of log N_e ≈ 2.8–4.6 dex.

Our study shows that the wide variation of local densities from point to point along the line of sight in Figures 6 and 7 is much more comprehensive than the variation of the integrated ones in Figure 8. The approaching part of the outer shell shows a relatively thinner arc shape with densities of log N_e ≈ 3.0–4.6 dex (see Figures 6(d) and (f)). The approaching outer shell is well defined in both spectral images and P-V maps. The receding part of the outer shell shows a broken outer shape. In Figure 6(b), the receding side of the main shell below the central star shows a well-defined bright primary form, which is also a denser region. The density range is about the same as that of the approaching part, log N_e ≈ 2.8–4.6 (or 4.7) dex.

The HST [N II] image in Figure 1 shows many bright small-scale features, all of which must be due to density enhancements in the optically thin NGC 7009. If the line of sight is unusually long, for example, if a considerably long path length appears at the edge of the spherical shell, we also expect a brightness enhancement (i.e., a bright rim). Apparently, the relatively fainter outer shell does not form a whole circle in the P-V density maps, especially in Figure 6(f). Figures 6(a)–(c) show that the receding part of the outer shell is relatively faint. The P-V density maps show that the receding part of the outer shell is not a perfect arc (see the weak-flux zone of the spectral images in Figures 6(a) and (c) and the S-SE and N-NW P-V density maps in Figures 6(d) and (f)).

According to Sabbadin et al. (2004, 2006), NGC 7009 is an optically thin PN that is powered by a luminous post-AGB star at a high temperature. The outer shell gas along the minor axis might have a change in its ionization state, as occurs naturally due to the greater distance of the outer shell from the source of ionizing radiation. Although S^+ is a minority ion throughout the main shell, it may be more abundant in the outer shell—perhaps the dominant ionization phase there.

### 3.2. Revised Expansion Velocities of the Two Shells

Sabbadin et al. (2004) constructed a 3D morphokinematical model structure based on detailed P-V diagrams and HST imagery. They assumed a general law of the expansion velocity, \( V_{\text{exp}} = c_1 \times R + c_2 \), where \( c_1 \) is the acceleration expansion slope; \( c_2 \) is the velocity at the center point when the velocity slope is extrapolated; and \( r \) is the spatial distance from the center to the line emission zone, which may be found from an observed distance of \( r \) projected onto the sky. The radial velocity variations of the main and outer shells obtained by Sabbadin et al. (2006) show a linear relation where \( V_{\text{exp}} = 4.0 \times r'' \) and \( 3.15 \times r'' \), respectively, which are extrapolated to the central star (\( c_2 \sim 0 \); see their Figure 5). Hyung et al. (2014) revised the \( V_{\text{exp}} \) by Sabbadin et al. (2006) with the various Keck HIRES spectral images and the HST images, which show a nonzero \( c_2 \) component for the main shell.

Steffen et al. (2009) also constructed a 3D morphokinematical model structure using the data by Sabbadin et al. (2004, 2006).
Their study generally confirmed the results of Sabbadin et al. (2006), but they found evidence of nonhomologous expansion velocities, i.e., a 10–15% deviation from a homogeneous radial expansion at the equatorial zone of the main shell. The P-V kinematic map in Figure 6 shows that the outer shell is distorted, as is the inner shell. Sabbadin et al. (2004) argue that the PA to get symmetric profiles is nearly 130°. As mentioned in previous studies such as Sabbadin et al. (2004) or Hyung et al. (2014; see their Figure 8), the expansion velocity variation of subshells over distance has been determined for the two main shells. Hyung et al. (2014) incorrectly calculated the radius and velocity of the outer shell based on the appearance of the inner bright shell. The kinematic center must be correctly reestimated considering the outer shell’s overall shape as well. In Figure 6(e), we added two (white and sky blue) vertical lines and one slightly slanted (sky blue line) the white vertical line, which indicates the position of the radial velocity of $-48.91 \text{ km s}^{-1}$, does not appear to be at the center of the two shells. Meanwhile, the newly estimated kinematic centroid (slanted sky blue line), which was derived by the general appearance of both ellipsoidal shapes, looks fine. The slanted sky blue line, which divides the inner shell velocity ellipse, corresponds to the median of the line profile shape (i.e., the kinematical center). As mentioned, the former radial velocity was derived based on the flux median of strong lines rather than the line shapes. The shape of the outer shell does not form a perfect ellipse. Still, the newly determined radial velocity, mainly by the main shell’s appearance, appears to be suitable for the outer shell.

Hyung et al.’s (2014) values should be reevaluated based on the latter centroid. Table 4 lists the expansion velocity versus the radius obtained by recalculating the radius shown in Table 4 of Hyung et al. (2014). The present kinematic centroid implies that the main [S II] subshell expands with $V_{exp}(\text{S II}) = 21.7 \text{ km s}^{-1}$, indicating that Hyung et al.’s (2014) expansion velocity (26.52 km s$^{-1}$) is overestimated by $\Delta V_{exp}(\text{S II}) = 4.82 \text{ km s}^{-1}$. Meanwhile, the outer [S II] subshell expands with $V_{exp}(\text{S II}) = 30.0 \text{ km s}^{-1}$, less than Hyung et al.’s (2014) estimate (42.14 km s$^{-1}$) by $\Delta V_{exp}(\text{S II}) = 12.14 \text{ km s}^{-1}$. Thus, we applied the velocity difference of $\Delta V_{exp}(\text{M}) = -4.82 \text{ km s}^{-1}$ to the expansion velocities of the stratified main subshells of the main shell and similarly, a difference of $\Delta V_{exp}(\text{O}) = -12.14 \text{ km s}^{-1}$ to those of the outer shell. We reestimated the radii based on the new kinematic center:

| Ion          | IP (eV) | R(Main) | $V_{exp}$(Main) | R(Out) | $V_{exp}$(Out) | S04 |
|--------------|---------|---------|----------------|--------|---------------|-----|
| He II        | 54.4    | 4.00    | 19.80          | ...    | ...           | 18.3|
| N III        | 47.4    | 4.32    | 19.34          | ...    | ...           | 20.0|
| [Ar IV]      | 40.7    | 4.62    | 19.19          | 10.99  | 24.34         | ... |
| [Cl IV]      | 39.6    | 4.67    | 19.86          | 11.02  | 25.36         | ... |
| [O III]      | 35.1    | 4.90    | 19.77          | ...    | ...           | 20.4|
| [Ar III]     | 27.6    | 5.22    | 19.86          | 11.42  | 25.88         | 20.4|
| He I         | 24.6    | 5.36    | 22.80          | ...    | ...           | 20.0|
| [S III]      | 23.3    | 5.41    | 19.98          | 11.56  | 26.50         | ... |
| [N II]       | 14.5    | 5.81    | 20.67          | 11.85  | 27.60         | 20.4|
| H I          | 13.6    | ...     | 20.09          | ...    | ...           | 20.8|
| [S II]       | 10.4    | 6.00    | 21.70          | 12.00  | 30.00         | 21.0|

Note. Radius units in Columns (3) and (5): arcseconds. Velocity units in Columns (4), (6), and (7): kilometers per second. The errors in $V_{exp}$ are less than 1.5 km s$^{-1}$. S04: The expansion velocities for the main shell by Sabbadin et al. (2004). *H I: $V_{exp}$ for the whole PN. See Hyung et al. (2014) and the text.

The main shell in Figure 6(e) implies that the radius of the main [S II] subshell is $6′$, the same as in Hyung et al. (2014), whereas the radius of the outer [S II] subshell, determined by Figures 6(d) and (f), decreases by 1′00 from 13′70 to 12′70. The radius of the outer [S II] subshell and all other subshells should be changed by $\Delta r = -1′00$, as shown in Column (5) of Table 4. The current estimate of the outermost radius of the outer shell is close to 11′8 by Sabbadin et al. (2004). Here, “M” and “O” represent the main and outer shells. Note that the derived expansion velocities agree better with those of Sabbadin et al. (2004).

Figure 9 shows the velocity data points and two linear regression fits excluding the He I and He II lines that best represent the scattering of the expansion velocities of the subshells responsible for each ion. Using the linear least-squares function (e.g., Microsoft Excel’s LINEST: $V = c_1 \times r^{c_2} + c_3$), the fitting yields to the main shell data $V_{exp}(\text{M}) = 1.20 \pm 0.25 \times r^{1.28} + 13.90 \pm 1.28 \text{ km s}^{-1}$ and to the outer shell data $V_{exp}(\text{O}) = 3.19 \pm 0.56 \times r^{0.56} - 10.36 \pm 6.37 \text{ km s}^{-1}$, where the value in parentheses is 1σ (see Figure 9). When finding the trend lines (or slopes), we excluded the He and H line velocities representing large areas. [S II] has a much larger deviation than the other lines. We also excluded the [S II] line for the outer shell. With [S II] included, the fitting gives a very unusual trend line, $V_{exp}(\text{O}) = 4.45 \pm 0.90 \times r^{0.90} - 24.41 \pm 10.28 \text{ km s}^{-1}$.

In the post-AGB evolutionary stage, it is known that the radiative pressure of the central star pushes the ejected shell, so the shell reaches a terminal velocity $V_t$ at a distance 10 times the AGB radius (Kwok 1981, 2000; Feibelman 2001). The linearity means that the acceleration mechanism seems to work after the shell leaves the central star. However, the $c_2$ value at the center are nonzero in both the inner main and outer shells. The main shell shows $c_2 = 13.90 \pm 1.28 \text{ km s}^{-1} (>0)$. Such a positive velocity at the center indicates a terminal velocity.
occurring in a post-AGB envelope at an early time or evidence of acceleration due to the hot bubble in the inner zone.

The intersection at the central position is related to the terminal velocity of the post-AGB. In contrast, the slope of the trend line is associated with the acceleration (+) or deceleration (−) of the expanding subshells. The slope of the outer shell expansion velocity intersects the zero velocity, $V_{exp}(O) ≈ 0$ (up to +2.38 km s$^{-1}$) within 2σ = 12.74 km s$^{-1}$. A simple positive terminal velocity and following continuous accelerations after post-AGB cannot accommodate such a negative velocity.

There is very little difference between the results here and those in Hyung et al. (2014): Both studies show that the main shell has a positive velocity intercept and the slopes of the relations are similar. The outer shell in the two studies has a velocity intercept compatible with zero at the center within 2σ, and the slopes show almost the same tendency. The radius of the outer shell and, as a result, the derived velocities are more similar to those of Sabbadin et al. (2004).

The 2D P-V density map from the HIRES spectral images along the major axis (Paper II, to be submitted) and the analysis by Steffen et al. (2009) and Sabbadin et al. (2004) show the presence of two torus shells at low latitudes near the equator, which are larger and faster than the presently studied equatorial outer shell. Both Sabbadin et al. (2004) and the present study show that the outer shell along the minor axis has a positive slope, i.e., a sign of acceleration. Perhaps, the fast stellar wind caused an acceleration of the main shell, but not of the outer shell at the equator, i.e., deceleration after acceleration.

Hyung et al. (2001) presented the case where NGC 6543 accelerated after reaching the terminal velocity after post-AGB. One likely interpretation is that the gradually increasing slope made it look as if the terminal velocity were negative. When the outermost shell was detached from the earlier post-AGB star, the subshells expanded at a relatively low (i.e., nearly zero) velocity, and as a result, the trend line reached a very small positive value near the center at that time. Later, when a second (now main) shell emerged from a hot central star, the former (now outer) shell experienced a relatively high acceleration (or it acquired a large slope of $c_1$) with the current weird acceleration pattern.

The expansion velocities of [S II] and other lines in Figure 9 are from the stratified subshells. Although they generally show Hubble-type acceleration in both the main and the outer shell, the kinematics of multiple shells is not included in the “interacting winds” theory by Kwok et al. (1978).

4. Conclusions

Using [S II] 6716/6731 Å and fixing the electron temperature $T_e = 10,000$ K, we derived densities of NGC 7009 along the minor axis with the Cloudy code by Ferland et al. (2017).

From the derived P-V maps of [S II] density, we were able to clearly distinguish two shells and find their densities and expansion velocities. Along the minor axis, the local density range of the main and the outer shell is log $N_e$ ∼ 2.8–4.6 dex. However, Figure 6(f) shows at least one region of log $N_e$ ∼ 4.7 dex in the inner main shell. The local densities derived from the 2D P-V map decomposed by radial velocities along the line of sight show a more considerable variation than those obtained from the integrated fluxes along the line of sight. The [S II] 6716/6731 Å ratio of the integrated spectrum for one pencil beam at the position of 4º indicates log $N_e$ ∼ 3.8 dex as shown in Table 3, whereas the 2D spectral image analysis shows that the density values have a range of log $N_e$ ∼ 2.8–4.5 dex for the same position, confirming that the actual density fluctuation is significant in the two main shells. While NGC 7009 is not a high-density PN, there appear to be local regions where the [S II] lines indicate high densities.

Since the densities of NGC 7009 shown by other lines are not all high, our results likely indicate that the higher density occurs at the outer boundary of the shell region rather than in the entire PN shell. Figures 6(a) and (c) show this very clearly, as there is [S II] emission from the volume between the two shells. Sabbadin et al. (2004) presented P-V maps for the [N II] line that also show a double-shell structure at the minor axis.

As mentioned earlier, NGC 7009 at PA = 169º (apparent minor axis) is an excellent example of an optically thin PN powered by a luminous post-AGB star at a high temperature (Sabbadin et al. 2006). The inner shell morphology may form due to the mass contrast, while the outer shell may form due to a change in ionization state. In any case, [S II] is a useful tracer of density wherever it is found in NGC 7009 or other PNe. Although the spectral images of the [S II] lines do not represent the whole system, they would provide many clues to the kinematics of the PN. Based on the new kinematic center, we derived the kinematics of the two shells.

In this study, we draw two basic conclusions. First, the local density has an extensive range along the line of sight compared to the derived mean value from the integrated flux. Second, a velocity jump exists between the two shells, and different kinematic characteristics appear in their acceleration mechanisms. Apparently, hot bubbles accelerated the main shell but had little effect on the outer part, especially on the outer shell along the minor axis. The well-known Hubble-type acceleration mechanism explains the expansion velocities of the main shell. However, the outer shell is not accommodated by such simple accelerations, suggesting that the physical state of the central star must have been very different in the past. Future studies also need to investigate how the slit spectral images of other low-excitation lines differ from the densities obtained on the integrated lines.

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Facilities: Keck: 10 m, High Dispersion Spectrometer.
Software: IRAF (Tody 1986, 1993), Starlink (Currie et al. 2014), Cloudy (Ferland et al. 2017).

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