Hu 1-2: a metal-poor bipolar planetary nebula with fast collimated outflows

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ABSTRACT

We present narrow-band optical and near-IR imaging and optical long-slit spectroscopic observations of Hu 1-2, a Galactic planetary nebula (PN) with a pair of [N II]-bright, fast-moving (>340 km s⁻¹) bipolar knots. Intermediate-dispersion spectra are used to derive physical conditions and abundances across the nebula, and high-dispersion spectra to study the spatio-kinematical structure. Generally Hu 1-2 has high He/H (≈0.14) and N/O ratios (≈0.9), typical of Type I PNe. On the other hand, its abundances of O, Ne, S, and Ar are low as compared with the average abundances of Galactic bulge and disc PNe. The position-velocity maps can be generally described as an hour-glass shaped nebula with bipolar expansion, although the morphology and kinematics of the innermost regions cannot be satisfactorily explained with a simple, tilted equatorial torus. The spatio-kinematical study confines the inclination angle of its major axis to be within 10° of the plane of sky. As in the irradiated bow-shocks of IC 4634 and NGC 7009, there is a clear stratification in the emission peaks of [O III], Hα, and [N II] in the northwest (NW) knot of Hu 1-2. Fast collimated outflows in PNe exhibit higher excitation than other low-ionization structures. This is particularly the case for the bipolar knots of Hu1-2, with He II emission levels above those of collimated outflows in other Galactic PNe. The excitation of the knots in Hu 1-2 is consistent with the combined effects of shocks and UV radiation from the central star. The mechanical energy and luminosity of the knots are similar to those observed in the PNe known to harbor a post-common envelope (post-CE) close binary central star.

Key words: ISM: abundances – ISM: jets and outflows – ISM: planetary nebulae: individual: Hu 1-2

1 INTRODUCTION

Planetary nebulae (PNe) represent the last stages in the evolution of low- and intermediate-mass stars, before they turn into white dwarfs. A large fraction of PNe presents complex morphologies, including axisymmetric shells, multipolar lobes, and collimated structures, in sharp contrast with the spherical envelopes typically seen around asymptotic giant branch (AGB) stars (e.g., Olofsson et al. 2010). somehow, the spherical AGB envelope is transformed into the complex PN shell. Hubble Space Telescope (HST) observations have led to the suggestion that the shaping of the most structured young PNe (or proto-planetary nebulae, proto-PNe) could be attributed to the action of high-speed collimated outflows or jets that operate during the late-AGB and/or early post-AGB phase, as they interact with the intrinsically spherical AGB circumstellar envelope (Sahai & Trauger 1998). These observations indicate that collimated outflows probably also play a crucial role in the shaping and dynamical evolution of PNe (e.g., Dennis et al. 2008 Huarte-Espinosa et al. 2012).

Collimated outflows or jet-like structures have been identified in a significant number of PNe. The origin of collimated outflows is still uncertain, although they are most likely related to the evolution of binary systems, the action of magnetic fields, or both (e.g., Soker 2006) De Marco 2009). Particularly, binary interactions that involve accretion (e.g., Soker 1998 Soker & Livio 1994) Reyes-Ruiz & López 1999) Nordhaus & Blackman 2006) Blackman & Lucchini 2014) have been considered to be a plausible engine to produce the ubiquitous collimated outflows in PNe and proto-PNe (e.g., Balick & Frank 2002). Recently, Tocknell, De Marco & Wardle 2014) constrained the physical properties of the common envelope (CE) interaction using the observed masses and kinematics of jets in four post-CE PNe.

Detailed studies of the spectra of jet-like structures in PNe are scarce, but they generally report strong low-excitation emis-

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emission lines (particularly from [N II]) combined with high-excitation emission lines (e.g., [O III]). Guerrero et al. (2008) Gonçalves et al. (2009). This notable difference with the spectra of the main nebular shells can be attributed to the combined contributions of ionizing photons from the central star and excitation by shocks. Therefore, these structures are candidates of irradiated shocks, i.e., bow-shocks that are illuminated by ionizing (stellar) fluxes from the post-shock direction (e.g., Hartigan, Raymond & Hartmann 1987).

Hu 1-2 (PN G086.5−08.8), first identified by Humason (1921) and classified as elliptical by Manchado et al. (1996), is a PN with fast, highly collimated outflows. Recently, Miranda et al. (2012a) identified two bipolar compact knots along the main axis of Hu 1-2 with bow-shock-like morphologies. An analysis of the radial velocities and proper motions of these knots showed that they move at velocities >340 km s\(^{-1}\). This velocity is much higher than the expansion velocities of the collimated outflows observed in most PNe (Guerrero et al. 2002). For instance, the bright “Saturn Nebula”, NGC 7009, has an elliptical main nebula with a pair of [N II]-bright outer knots along its major axis (e.g., Gonçalves et al. 2003). Despite the morphological similarities with Hu 1-2, the expansion velocity of ∼60 km s\(^{-1}\) reported for the bipolar knots of NGC 7009 (Reay & Atherton 1985) is much lower than that observed in Hu 1-2, although we recall that the expansion velocity of the knots in NGC 7009 is quite uncertain (Gonçalves et al. 2003).

The high-velocity and bow-shock-like morphology led Miranda et al. (2012a) to conclude that these knots probably represent bow-shocks associated to high-velocity bullets. Furthermore, a preliminary analysis of narrow-band images of the knots suggests that [N II] peaks farther away from the central star than [O III] (Miranda et al. 2012b). The enhanced [N II] emission in the knots seems to imply shock-excitation, whereas the strong [O III] emission rather points to irradiation from the central star. A comprehensive analysis of the emission spectrum of the knots is crucial to determine the excitation mechanism, as done by, e.g., Riera et al. (2005) for Hen 3-1475 and Guerrero et al. (2008) for IC 4634.

The physical structure of its main nebular shell is also largely unknown. Narrow-band [N I] image (Miranda et al. 2012a) reveals a complex morphology for its innermost regions, which adds to the peculiar velocity field revealed by kinematical studies (Sabadin, Bianchini & Hamzaoglu 1983 Sabbadin, Cappellaro & Turatto 1987). Similarly, the kinematical structure of the faint bipolar lobes is completely unknown. The relatively large He/H and N/O abundance ratios of the bright inner regions of Hu 1-2 qualify it to be Type I PN (Peimbert & Torres-Peimbert 1987), but detailed analysis of the α elements (oxygen, neon, sulfur and argon) are much lower than those in most other Galactic PNe. This peculiar abundance pattern may shed light on the origin and evolution of Hu 1-2, but a spatially-resolved study of the physical conditions, chemical abundances, and excitation mechanisms is lacking.

In this paper we present high spatial resolution narrow-band optical and near-infrared images and high- and intermediate-dispersion long-slit optical spectra of Hu 1-2. These data have allowed us to carry out a complete analysis of its spatio-kinematical properties and physical conditions, abundances, and excitation mechanisms. Particular emphasis is made in the investigation of the properties of the collimated outflows in Hu 1-2.

| Telescope | Instrument | Filter | \(\lambda_c\) | \(\Delta\lambda\) | Exp. Time (s) |
|-----------|------------|--------|-------------|--------------|--------------|
| NOT       | ALFOSC     | [O III] | 5007 Å      | 30 Å         | 600          |
|           |            | H\(\alpha\) | 6567 Å | 8 Å | 600           |
|           |            | [N II]  | 6588 Å | 9 Å | 900           |
| TNG       | NICS       | Br\(\gamma\) | 2.169 μm | 0.035 μm | 1200         |
|           |            | H\(\alpha\) | 2.122 μm | 0.032 μm | 1200         |
|           |            | K\(\alpha\) | 2.275 μm | 0.039 μm | 1200         |

2 OBSERVATIONS

2.1 Imagery

Narrow-band optical images in the [O III], H\(\alpha\), and [N II] emission lines were acquired on 2008 September 2 using the Andalucía Faint Object Spectrograph and Camera (ALFOSC) on the 2.5m Nordic Optical Telescope (NOT) of the Observatorio del Roque de los Muchachos (ORM) on the island of La Palma (Spain). The characteristics of the narrow-band filters used in these observations (central wavelength \(\lambda_c\) and bandwidth \(\Delta\lambda\)) are summarized in Table 1. An EEV 2k×2k CCD was used as detector, yielding a plate scale of 0′′.184 pixel\(^{-1}\) and a field of view (FoV) of 6′3×6′3.

Two images in each filter were obtained with a small dithering between them to eliminate cosmic rays and reduce cosmic defects of the CCD. The images were bias-subtracted, flat-fielded by twilight flats, and combined using standard IRAF\(^\text{1}\) IDL2.14.1 routines. The spatial resolution of the final images, as derived from the FWHM of stars in FoV is 0′′7.

The three images were then background-subtracted and flux-calibrated using the H\(\alpha\), [N II] \(\lambda\lambda 6583\) and [O III] \(\lambda\lambda 5007\) line fluxes measured in the intermediate-dispersion spectrum that will be presented in Section 2.2. The individual flux-calibrated narrow-band images of Hu 1-2 are presented in Figure 1 whereas a color-composite picture is displayed in Figure 2. In Figure 3 we present a close-up of the [N II] emission from the inner region of Hu 1-2.

Narrow-band, near-infrared (IR) images were obtained on 2004 July 11 with the 3.5m Telescope Nazionale Galileo (TNG) also at the ORM. The Near-Infrared Camera and Spectrograph (NICS) was used with a 1024×1024 Rockwell HgCdTe array. The spatial scale is 0′′.13 pixel\(^{-1}\) and the FoV is 2′2×2′2. The images were obtained through Br\(\gamma\), H\(\alpha\) and continuum \(K\(\alpha\)\) filters whose central wavelengths and bandwidths are given in Table 1. The images were reduced with the MIDAS\(^2\) package following standard procedures for near-IR image reduction. The spatial resolution of the final images, as derived from the FWHM of field stars in the FoV, is 0′′75. Figure 4 presents the three near-IR images.

2.2 Intermediate-dispersion spectroscopy

Intermediate-dispersion spectra of Hu 1-2 were obtained on 2011 October 9, using the ALBIREO spectrograph at the 1.5m telescope.
Fast outflows in the metal-poor PN Hu 1-2

Figure 1. Nordic Optical Telescope (NOT) ALFOSC flux-calibrated grey-scale images of Hu 1-2 in H\textalpha\ (left), [N II] (middle) and [O III] (right). The 2.5′-wide long slit along PA ≈320° used for the intermediate-dispersion spectroscopy (see Section 2.2) was placed across the northwest (NW) and southeast (SE) knots as indicated by long-dashed lines in the H\textalpha\ image, where the slit apertures used to extract 1-D spectra for the inner and outer regions are indicated by the heavy white and black dashed boxes (10′′ each in length), respectively. The NW and SE knots, as well as a field star partially superimposed on the SE knot, are indicated in the [N II] image, where the two slit positions used for high-dispersion spectroscopy (see Section 2.3) are indicated with two black lines (slit width not to scale). The “spikes” along the north-south direction in the [O III] image are stray light due to the very strong [O III] emission from the inner region of Hu 1-2. Images are scaled to the same level and the grey levels are in logarithm. The white contours over-plotted in the central regions correspond to 2.5 \times 10^{-14}, 1.0 \times 10^{-14}, 5.0 \times 10^{-15}, and 1.0 \times 10^{-15} erg cm^{-2} s^{-1} arcsec^{-2}. The color bar below shows the grey scale in surface brightness (in erg cm^{-2} s^{-1} arcsec^{-2}).

of the Observatorio de Sierra Nevada (OSN), Granada, Spain. A Marconi 2048×2048 CCD was used as a detector, in conjunction with the 400 lines mm^{-1} grating #4 blazed at 5500 Å. The slit length was \sim 6′ and its width was set at 50 μm (\sim 2.5′′). A 2×2 binning in the detector was used, implying plate and spectral scales of 1′′.53 pixel^{-1} and 3.54 Å pixel^{-1}, respectively. The spectral resolution was \sim 4.7 Å, and the wavelength uncertainty \sim 1 Å. The spectral coverage is 3570–7200 Å. The seeing, as determined from the FWHM of the continuum of field stars covered by the slit, was \sim 3′′. As illustrated in Figure 1- left, the slit was aligned along a position angle (PA) of 320°, i.e., along the major nebular axis and through the bipolar knots.

Three 60 s and six 300 s exposures were obtained to secure information both from the bright and faint emission lines in this nebula; indeed, the bright [O III] λ5007 emission line was found to saturate in the central regions of the nebula in the long exposures. All the spectra were bias-subtracted, flat-fielded, wavelength and flux calibrated, following standard procedures using IRAF. Spectra of the spectrophotometric standard star Feige 115 acquired on the same night were used to carry out the flux calibration.

2.3 High-dispersion spectroscopy

Two high-dispersion, long-slit spectra of Hu 1-2 were obtained in 2004 June with IACUB3 on the 2.5m NOT at ORM. The slit positions, oriented at PAs 30° and 320°, are shown in Figure 1-middle. The long-slit spectra at PA 320° was already presented by Miranda et al. (2012a) in the analysis of the kinematics of the bipolar knots. The H\textalpha\ and [N II] λλ6548, 6583 emission lines were observed with a slit width of 0′.65 for an exposure of 900 s. The spectral resolution (FWHM) is 8 km s^{-1}, and the spatial resolution is \sim 1′′. See Miranda et al. (2012a) for a detailed description of these observations.

Figure 2. Color-composite picture of Hu 1-2 in the [N II] (red), H\textalpha\ (green), and [O III] (blue) emission lines. All intensities are displayed in logarithmic scale. A field star is partially superimposed on the southeast (SE) knot.
The optical narrow-band images in Figure 1 show that Hu 1-2 has a bright point-like central source (as can be seen in Figure 1) over-plotted with contours, showing the complex knotty structure in its central regions. The image is centered on the central star (as can be seen in Figure 1). Grey scale is in logarithm and the contour levels are arbitrary.

3 MAIN NEBULA

3.1 Morphology

The optical narrow-band images in Figure 1 show that Hu 1-2 has an elongated elliptical or slightly bipolar main nebula with a size of $\sim 12'' \times 32''$ with the major axis oriented at PA $\sim 320^\circ$, and a pair of bipolar knots (NW and SE) located along the main nebular axis, each $\sim 27''$ away from the central star. As already noted by Miranda et al. (2012a), the SE knot is partially superimposed by a field star and cannot be well studied. At any rate, the high-resolution NOT images reveal that the knots (in particular the NW one) present bow-shock morphology (Figure 1). In the central region of Hu 1-2, there is a bright, z-shaped structure (hereafter the inner region) with a size of $\sim 10'' \times 10''$ (Figure 1 middle; see also description below). The bipolar lobes are considerably fainter than the inner region. Moreover, the lobes harbor a noticeable richness of small structures that differ from each other. The NW lobe seems to be composed of two concentric structures, a NW inner lobe and a NW outer lobe, that are better observed in the H$\alpha$ image. Only part of the NW outer lobe can be recognized in the [O III] image, where it shows a clearly curly morphology, and in the [N II] image, where the [N II] emission is mainly detected in a couple of very compact regions. A SE counterpart of the NW inner lobe can be recognized, also exhibiting a remarkable curly structure in the [O III] image. No SE counterpart of the NW outer lobe can be identified. Instead, several knots are observed in the [O III] image, that are oriented along (or close to) the main nebular axis. Faint [N II] emission is detected at the leading head of these knots.

A close inspection of the inner region of Hu 1-2 in the [N II] image reveals a peculiar structure, as shown in Figure 1. It shows an arc-shaped central “bar” with a size $\sim 6''$ oriented at PA $\sim 30^\circ$ that contains two bright knots separated by $\sim 2''$. There is enhanced emission and/or knots on either end of the bar that seem to trace the edges of bipolar lobes towards the east and west. As a whole, the inner region of Hu 1-2 exhibits a remarkable point-symmetric structure. It is worth noting that none of the point-symmetric pairs of knots is oriented along the major nebular axis. It is tantalizing to interpret the inner region as a broken equatorial torus, but we have to admit that such a torus would be broken in a very point-symmetric manner. The kinematics of this region, to be described in Section 3.2, is less compatible with that expected from a simple ring-like equatorial torus.

The optical images (Figures 1 and 2) show that [N II] emission is enhanced in the knots and in the inner region while the bipolar lobes (hereafter the outer region) are dominated by the H$\alpha$ line emission. The strongest [O III] emission comes from both the main nebula and regions behind the head of the knots facing toward the central star.

The point-symmetric inner region is also enhanced in the near-IR emission, as shown in Figure 3, where it presents a very similar morphology to that observed in the optical ones. In addition, faint emission from the bipolar lobes can be recognized in the Br$\gamma$ filter. The H$\beta$ emission is faint, but definitely present in the NW knot and, possibly, also in the SE counterpart. We have tried to subtract the continuum image from the emission-line images (the subtracted images are not shown here), and found that Br$\gamma$ emission is present in the inner region and bipolar lobes whereas in the case of H$\beta$, no satisfactory subtraction was achieved; nevertheless, the presence of H$\beta$ emission in the inner region is doubtful as the emission in the H$\beta$ image can be attributed to continuum emission. Finally we note that both the $K_c$ and H$\alpha$ images show a faint point-like source at the center of the inner region (Figure 1), which could be the central star of Hu 1-2. This point-like source is not well observed in the Br$\gamma$ image probably due to the relatively stronger line emission. In all three near-IR filters, we observed an emission feature located towards the SW of the central point-like source (better seen in Figure 1 right). A comparison between the NOT ALFOSC [N II] and TNG NICS $K_c$ images shows that the SW feature in the $K_c$ image is associated with the SW [N II] knot in the central bar. The $K_c$ knot peaks closer to the central star by $\sim 0''$.3, suggesting that it corresponds to ionized material with higher excitation than the [N II] line.

3.2 Kinematics

The grey-scale position-velocity (PV) maps of the H$\alpha$ and [N II] $\lambda 6583$ emission lines derived from the high-resolution, long-slit spectra at PA $50^\circ$ and $320^\circ$ are shown in Figure 5. The PV map of the He II $\lambda 6560$ emission line is close to that of H$\alpha$. The PV map of the [N II] line at PA $320^\circ$ was already presented by Miranda et al. (2012a, Figure 2 therein), who focused on the emission features associated with the bipolar knots. We examine in detail the kinematical structure of the main nebula instead. In the following, radial velocities will be quoted with respect to the heliocentric systemic velocity of $\sim 3.3 \, \text{km s}^{-1}$ for Hu 1-2 that we deduced from our high-dispersion spectra (see below).

The [N II] PV map at PA=$320^\circ$ shows two compact features at $\pm 0.5''$ from the center with radial velocities $\pm 38 \, \text{km s}^{-1}$, with present point-symmetric, arc-like shapes, with the NE feature redshifted, and the SW one blueshifted. The emission peaks in these features are located at $\pm 1.9''$ from the center and their radial velocity amounts to $\pm 30 \, \text{km s}^{-1}$. At larger distances from the center, the radial velocity in the features remains approximately constant; at smaller distances the radial velocity increases up to $\sim -48 \, \text{km s}^{-1}$ at $\pm 0.3''$ from the center in the blueshifted feature and up to $\sim +43 \, \text{km s}^{-1}$ in the redshifted feature.
km s$^{-1}$ at 1\textdegree{}5–3\textdegree{}2 from the center in the redshifted feature. This morphology in the PV diagram indicates a rotation of the torus. If the inner structure is/was indeed a ring (or torus), then it could have been distorted by some agent such as several bipolar ejections along different directions, as suggested by the point-symmetry of the bright regions. If this is the case, the kinematics cannot be interpreted easily. An isolated knot is also observed at $-43$ km s$^{-1}$ and 2\textdegree{}5 (Figure 5), which reflects the complexity of the inner structure.

These [N II] features are generally consistent with the brightest features in the H$\alpha$ PV maps. The arc shape of the [N II] features in the PV map at PA 50\degree{} can also be recognized in H$\alpha$ with radial velocities about 5 km s$^{-1}$ lower than those measured in the [N II] emission line. In the H$\alpha$ PV map, these features are embedded or superimposed on a broad and faint H$\alpha$ component that extends to $\pm 12\arcsec$ and $\pm 130$ km s$^{-1}$ in radial velocity. The broad H$\alpha$ emission is mostly symmetrical with respect to the velocity axes. At PA 320\degree{} the extended H$\alpha$ emission is observed up to a distance of 12\arcsec{} on both sides of the center. This emission corresponds to the elliptical/bipolar lobes of the nebula. Although the emission is very faint in the PV maps, the observed kinematics appears compatible with that expected from an hour-glass nebula. The total spatial extent of the H$\alpha$ emission detected in the PV maps (12\arcsec{} $\times$ 24\arcsec{}) coincides very well with the spatial extent of the main nebula observed in direct images.

Two bright features are detected in the He II emission line at both PAs. Their radial velocity separation amounts to $\simeq 33$ km s$^{-1}$, while their spatial separation is $\simeq 1\arcsec$7 at PA 50\degree{} (where they present a slight spatial elongation) and $\simeq 0\arcsec$4 at PA 320\degree{} (Figure 5). The brightest features in each of the three emission lines and their spatio-kinematical properties indicate that they probably trace a unique structure that is related to the bright inner region of Hu 1-2.

It has been shown that differing the systemic velocities ($v_{\text{sys}}$) of the main nebular shell and collimated outflows can be associated to the presence of a binary central star (e.g., Miranda et al. 2001). Using our high-dispersion spectra of Hu 1-2, we measured the heliocentric systemic velocities of the main nebula and the knots: $v_{\text{sys}}$ (nebula) = $-3.3 \pm 1.7$ km s$^{-1}$, and $v_{\text{sys}}$ (knot) = $+1.4 \pm 2.5$ km s$^{-1}$. These two systemic velocities agree within the errors and, therefore, they cannot confirm whether a binary central star exists or not. We note that our measurement of the nebular systemic velocity are consistent, but not completely coincident, with previous measurements: $-9.0 \pm 8.1$ km s$^{-1}$ (Schneider et al. 1983) and $+9.0 \pm 4.3$ km s$^{-1}$ (Durand et al. 1998). These differences most likely reflect the complex kinematical structure of the main nebular shell of Hu 1-2, which makes difficult a precise estimate of the systemic velocity based on spatially unresolved observations.

### 3.3 Spatio-kinematical model

The H$\alpha$ PV map at PA 320\degree{} is similar to that found in other bipolar nebula (e.g., Kn 26; Guerrero et al. 2013) suggesting bipolar expansion. We have adopted the prescription by Solf & Ulrich (1985) to model a bipolar outflow, where the radial velocity ($v_r$) at a latitude angle ($\phi$) above the equatorial plane is given by

$$v_r(\phi) = v_p + (v_p - v_c) \times \sin^\gamma(\phi)$$

where $v_p$ and $v_c$ are the polar and equatorial velocities, respectively, and $\gamma$ is a parameter to fit the specific shape of the hour-glass. We note that the PV map suggests a small inclination angle with respect to the plane of the sky. Figure 6 shows three hour-glass models at inclination angles of 10\degree{}, 5\degree{}, and 0\degree{}, each assuming that $v_p$ and $v_c$ are 150 and 30 km s$^{-1}$, respectively, and a polar radius ($R_p$) of 12\arcsec{}5. By varying the parameter $\gamma$ we obtained the best fit model for the PV map.

It is clear from Figure 6 that no ideal representation of the kinematics can be reached. Whereas one particular set of parameters explains the observed kinematics of a given region (e.g., the front side of the SE lobe and the rear side of the NW lobe), other parameters are needed to reproduce the observed kinematics of other nebular regions (e.g., the rear side of the SE lobe and the front side of the NW lobe). This is not surprising because the images
Figure 5. Grey-scale PV maps of the He II and Hα lines (left) and the [N II] line (right). In the left panels, the two weak features bluewards of Hα belong to the He II λ6560 line. The slit PA = 320° and 50° (see Figure 1-middle) are shown in the upper and lower panels, respectively.

Figure 6. Grey-scale PV map of the Hα emission line at PA = 320°. A smoothing with a 3×3 pixel box has been applied to the original PV map (see also Figure 5). The over-plotted white contours define the position of the two emission maxima. Also over-plotted are three hour-glass models (v_p = 150 km s^{-1}, R_p = 12.5′′) with different inclination angles of the polar axis with respect to the plane of the sky, θ, and the model parameter γ (see Equation [1]): θ = 10° and γ = 2.5 (red solid line), θ = 5° and γ = 3.5 (blue dotted line), and θ = 0° and γ = 4.5 (green dashed line).

already suggest noticeable morphological differences between the two lobes, and these are reflected into differences in their intrinsic kinematics. From our analysis we conclude that a reasonable upper limit for the inclination angle of the polar axis is 10° and an approximate value for the polar expansion velocity is 150 km s^{-1}. Assuming a lower limit of 3.5 kpc for the distance to Hu 1-2 (Miranda et al. 2012a), we derived a lower limit ≃1100 yr for the kinematical age of the bipolar lobes, which is consistent with the value of 1375^{+320}_{-590} yr obtained for the bipolar knots (Miranda et al. 2012a).

The [N II] features in the PV maps could be due to a tilted torus (or ring-like structure). If we assume a diameter of 10′′ for the equator and a projection of 1′′ due to tilt, an inclination angle ≃6° is obtained for the plane of the ring with respect to the line of sight. This value is compatible with the inclination angle of the bipolar lobes. However, the observed kinematics strengthens the idea that the inner regions of Hu 1-2 is difficult to be interpreted as a simple equatorial torus. In particular, for a torus oriented at PA ≃50° and seen almost edge on, a long-slit spectrum along PA ≃50° should show a velocity ellipse with maximum splitting at the center and decreasing towards the edges of the torus. The PV map at PA ≃50° (Figure 5) shows a very different structure. A possible interpretation for the inner region is that a series of bipolar ejections at different directions have been involved in its formation, distorting a previous, more defined structure.

4 SPECTRAL ANALYSIS

One-dimensional (1-D) spectra of the bright inner region, the bipolar lobes, and the bipolar knots were extracted with the spatial ex-
| $\lambda_{\text{obs}}$ ($\AA$) | Inner Region | Outer Region | NW Knot | Ion | Mult. | $\lambda_{\text{lab}}$ ($\AA$) | Lower | Upper | $g_1$ | $g_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 3726.2$^a$ | 47.8 | 75.2±2.5 | 14.7 | 23.1±1.5 | 347 | 545±34 | [O II] | 3727 | 2p$^3$ 3p$^5$ | 2p$^3$ 2D$^0$ | 4 | 4 |
| 3749.5 | 2.11 | 3.30±0.35 | | | | | | | | |
| 3757.8$^b$ | 1.87 | 2.91±0.32 | 4.65 | 7.2±0.8 | | | | | |
| 3769.9 | 2.89 | 4.5±0.5 | | | | | | | |
| 3797.1 | 3.78 | 5.8±0.6 | | | | | | | |
| 3815.9 | 1.08 | 1.7±0.4 | 12.9 | 20±5 | | | | | |
| 3834.4 | 5.19 | 7.9±0.5 | | | | | | | |
| 3868.0 | 50.8 | 76.5±1.3 | 29.5 | 44.4±1.8 | | | | | |
| 3888.0$^c$ | 12.3 | 18.5±0.7 | 12.6 | 18.9±0.7 | | | | | |
| 3922.0 | 0.52 | 0.78±0.21 | | | | | | | |
| 3967.5$^d$ | 26.5 | 38.6±1.2 | 18.7 | 27.3±1.8 | 80.6 | 117±8 | [Ne III] | 3967 | 2p$^3$ 3p$^4$ | 2p$^3$ 2D$^0$ | 3 | 5 |
| 4024.8 | 1.68 | 2.40±0.35 | | | | | | | |
| 4067.9 | 3.67 | 5.1±0.5 | | | | | | | |
| 4100.4$^e$ | 18.0 | 24.9±0.46 | 17.6 | 24.3±1.0 | 38.0 | 52.5±2.2 | He I | 4101 | 2p$^3$ 2D$^0$ | 6d 2D | 8 | 7 |
| 4143.9 | 0.211 | 0.29±0.13 | | | | | | | |
| 4198.2 | 1.26 | 1.67±0.25 | | | | | | | |
| 4226.7 | 0.24 | 0.32±0.10 | | | | | | | |
| 4340.0 | 38.1 | 47.5±1.2 | 30.3 | 37.7±1.9 | 34.2 | 42.6±2.3 | [O III] | 4340 | 2p$^3$ 3p$^4$ | 5d 2D | 8 | 5 |
| 4362.5 | 14.6 | 18.0±0.6 | 7.82 | 9.6±0.6 | | | | | |
| 4386.6 | 0.36 | 0.44±0.10 | | | | | | | |
| 4470.9 | 2.31 | 2.72±0.21 | | | | | | | |
| 4541.2 | 2.94 | 3.35±0.19 | | | | | | | |
| 4640.8 | 1.92 | 2.1±0.8 | | | | | | | |
| 4685.6 | 88.6 | 95.0±2.1 | 117 | 126±6 | 132 | 142±6 | He II | 4686 | 2p$^3$ 3p$^4$ | 4f 2D$^0$ | 18 | 3 |
| 4711.3 | 8.25 | 8.8±0.8 | 7.76 | 8.2±1.1 | | | | | |
| 4725.6 | 1.84 | 1.9±0.7 | | | | | | | |
| 4740.2 | 5.80 | 6.09±0.25 | 5.83 | 6.1±0.5 | | | | | |
| 4861.6$^f$ | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | | |
| 4921.8 | 0.70 | 0.7±0.5 | | | | | | | |
| 4959.3 | 252 | 243±3 | 168 | 162±2 | 408.31 | 394±8 | [O III] | 4959 | 2p$^3$ 2D$^0$ | 2p$^3$ 2D$^0$ | 3 | 5 |
| 5007.0 | 775 | 735±5 | 516 | 489±4 | 1109.88 | 1053±11 | [O III] | 5007 | 2p$^3$ 2D$^0$ | 5d 2D | 5 | 5 |
| 5145.5 | 0.30 | 0.27 | | | | | | | |
| 5176.9 | 0.25 | 0.22 | | | | | | | |
| 5198.7$^g$ | 2.02 | 1.8±0.25 | | | | | | | |
| 5275.9 | 0.21 | 0.18 | | | | | | | |
| 5335.6 | 0.30 | 0.26 | | | | | | | |
| 5412.0 | 8.71 | 7.3±0.5 | 8.09 | 6.8±0.9 | | | | | |
| 5483.8 | 0.14 | 0.11 | | | | | | | |
| 5516.4 | 0.56 | 0.46±0.14 | | | | | | | |
| 5558.3 | 0.74 | 0.60±0.14 | | | | | | | |
| 5630.0 | 0.14 | 0.11 | | | | | | | |
| 5678.1 | 0.25 | 0.20 | | | | | | | |
| 5721.4 | 0.90 | 0.70±0.17 | | | | | | | |
| 5755.4 | 5.73 | 4.42±0.19 | | | | | | | |
| 5876.2 | 12.3 | 9.2±0.5 | | | | | | | |
| 6037.9 | 0.18 | 0.13±0.14 | | | | | | | |
| 6072.8 | 0.24 | 0.18±0.16 | | | | | | | |
| 6086.2 | 1.61 | 1.16±0.15 | | | | | | | |
| 6101.3 | 0.42 | 0.30±0.10 | | | | | | | |
| 6117.9 | 0.32 | 0.23±0.13 | | | | | | | |
| 6169.9 | 0.31 | 0.22±0.12 | | | | | | | |
| 6232.5 | 0.49 | 0.34±0.14 | | | | | | | |
| 6300.3 | 8.52 | 5.89±0.25 | | | | | | | |
| 6311.8$^h$ | 5.02 | 3.47±0.14 | 4.51 | 3.11±0.19 | | | | | |
| 6363.6 | 2.68 | 1.83±0.11 | | | | | | | |

Table 2. Emission lines detected in the inner region, outer region, and NW knot of Hu 1-2. The observed fluxes and the extinction corrected intensities are all normalized to Hβ = 100. The colon “;” indicates a large uncertainty in the line intensity. Logarithm of the total observed Hβ fluxes measured from the 1-D spectra extracted from the slit apertures shown in Figure 4 left are given at the bottom of the table.
Continued.

The contamination shown in the Hα image in Figure 4(left). The contamination by a background star with absorptions in the hydrogen Balmer lines renders little use of the spectrum of the SE knot. The I-D spectra showed scattered light from the bright inner region of the H3+[O iii] and Hα+[N ii] lines. As a result, the I-D spectra displayed a pedestal of emission under the [O iii] and Hα+[N ii] lines. We removed this dispersed light by fitting a long-pass Gaussian profile to the nebular continuum around these lines. After this correction, the [O iii] λ5007/λ4959 and [N ii] λ6583/λ6548 line ratios measured from the spectra are both close to their theoretical value of \( \sim 3 \). The corrected I-D spectra are shown in Figure 7.

We also integrated total fluxes of the [O i] |λ5007, [N ii] λ6583, and Hα emission lines for the main nebula and estimated the surface brightnesses. The brightness values were used to calibrate the ALFOSC narrow-band images of Hu 1-2 (Section 2.1).

### 4.1 Physical conditions

The I-D intermediate-dispersion, normalized spectra of the inner region, outer region, and NW knot of Hu 1-2 are shown in Figure 7. Although at intermediate-dispersion, the long slit spectrum of Hu 1-2 presented here proves to be very deep. The signal-to-noise ratio (S/N) of the spectrum of the inner region is particularly high, and thus many weak emission lines with fluxes lower than 1% of Hβ are detected (see Figure 7). The emission lines detected in the spectra of the three regions are compiled in Table 2.

We derived a logarithmic extinction parameter, \( c(Hβ) \), of 0.61 in the inner region of Hu 1-2 using the observed Hα/Hβ line ratio. Here the theoretical Hα/Hβ line ratio was adopted from Storey & Hummer (1995), assuming an electron temperature of 10 000 K and a density of \( 10^4 \) cm\(^{-3} \). Our \( c(Hβ) \) value agrees with 0.60 given by Pottasch et al. (2003) also Hyung, Pottasch & Feibelman 2004., who carried out echelle spectroscopy at the center of Hu 1-2 with a slit entrance \( 1'' \times 2'' \), i.e., also the inner region of Hu 1-2. Earlier observations by Peimbert & Torres-Peimbert (1987) and Aller & Czyzak (1979) gave an extinction value of 0.64 and 0.61, respectively. The \( c(Hβ) \) values derived for the outer region and the NW knot are \( \sim 0.40 \) and 0.90, respectively. Given the more accurate emission-line measurements for the inner region, we adopted 0.61 as the extinction in all three regions of Hu 1-2, although we cannot totally rule out the possibility that extinction in the NW knot could be higher. The extinction law of Whitford (1958) was used to apply this correction. We found that the use of different extinction laws (e.g., Whitford 1958, Savage & Mathis 1979, Cardelli, Clayton & Mathis 1989) results in differences in the extinction-corrected fluxes of emission lines in the optical range from \( \sim 3700 \) Å to 7100 Å lower than 5%.

The extinction-corrected relative line intensities, \( I(λ) \), together with the estimated errors, are given in Table 2. Errors in the line intensities were estimated from multiple measurements of the observed fluxes, through the almost linear relation between the two quantities,

\[
I(λ) = 10^{\left(\frac{β}{2}\right)} f(λ) F(λ),
\]

where \( f(λ) \) is the reddening function, normalized to \( f(β) = 0 \), adopted from Whitford (1958). Uncertainties in the extinction func-

### Table 2. Continued.

| \( λ_{\text{obs}} \) (Å) | Inner Region | Outer Region | NW Knot |
|-----------------|-------------|--------------|---------|
| \( F(λ) \) | \( I(λ) \) | \( F(λ) \) | \( I(λ) \) | \( F(λ) \) | \( I(λ) \) | \( \text{Ion} \) | \( \text{Mult.} \) | \( \lambda_{\text{lab}} \) (Å) | Lower | Upper | \( g_1 \) | \( g_2 \) |
|-----------------|-------------|--------------|---------|
| 6045 4 | 0.72 | 0.49±0.11 | He II | 6406 | 5g 2G 15h 2H \( \oplus \) | 50 |
| 6434 1 | 2.70 | 1.82±0.12 | [Ar iv] | 6355 | 3p 2P 3p 2D | 3 | 5 |
| 6526 1 | 0.75 | 0.50±0.12 | [N ii] | 6557 | 2p 2P 3p 1D | 1 | 5 |
| 6547 5 | 77.1 | 51±5 | [N ii] | 6548 | 2p 2P 3p 2D | 3 | 5 |
| 6566 9 | 468 | 339±20 | [N ii] | 6563 | 2p 2P 3p 2D | 8 | 18 |
| 6582 9 | 248 | 162±5 | [N ii] | 6583 | 2p 2P 3p 2D | 5 | 5 |
| 6678 3 | 4.13 | 2.7±0.4 | He I V46 | 6678 | 2p 2P 3p 2D | 3 | 5 |
| 6715 7 | 7.51 | 4.8±0.22 | [S ii] | 6716 | 2p 3S 2D | 4 | 6 |
| 6730 5 | 12.7 | 8.1±0.25 | [S ii] | 6731 | 2p 3S 2D | 4 | 4 |
| 6820 9 | 0.52 | 0.33±0.12 | [Fe v] | 6819 | 3d 2P 4 3d 2S 4 | 1 | 3 |
| 6889 8 | 1.13 | 0.70±0.14 | He II | 6891 | 5g 2G 12h 2H \( \oplus \) | 50 |
| 7004 8 | 6.43 | 3.90±0.20 | [Ar v] | 7006 | 3p 2P 3p 2D | 5 | 5 |
| 7065 2 | 7.22 | 4.33±0.24 | He I | 7065 | 2p 3P 3s 2S | 9 | 3 |

\( \text{a} \) A blend of the [O ii] \( \lambda\lambda3726, 3729 \) lines.

\( \text{b} \) Blended with the O iii \( \lambda3760 (3s^2P^2_2 - 3p^2D^2_1) \) line.

\( \text{c} \) Blended with the He i \( \lambda3888 (2s^2S - 3p^2P^0) \) line.

\( \text{d} \) Blended with the H i \( \lambda3970 (2p^2P^0 - 7d^2D) \) line.

\( \text{e} \) Blended with the N iii \( \lambda4103 (3s^2S^2_1 - 3p^2P^0_1/2) \) line.

\( \text{f} \) Blended with He ii \( \lambda4869 \) line, whose flux contribution is negligible. The same happens to Hα, whose is blended with He ii \( \lambda6560 \) line. See the text for details.

\( \text{g} \) Blended with the [N i] \( \lambda5200 (3s^2S^0/2 - 3p^2D^0/2) \) line.

\( \text{h} \) Corrected for the flux of the blended He ii \( \lambda6311 (5g 2G - 16h 2H \oplus) \) line.

\( \text{i} \) Corrected for the flux of the blended He ii \( \lambda6683 (5g 2G - 13h 2H \oplus) \) line.

\( \text{j} \) \( \text{erg cm}^{-2} \text{s}^{-1} \) in our extracted spectra.
Figure 7. One-dimensional intermediate-dispersion optical spectra of the inner region (a and b), outer region (c), and NW knot (d) of Hu 1-2 in the spectral range 3700–7100 Å. Panel (b) is a zoom-in view of panel (a) highlighting the weakest emission lines detected in the inner-region spectrum. All spectra have been normalized such that H$\beta$ has an integrated flux of 100. Extinction has not been corrected for. Spectra are scaled to fit the peak intensity of the H$\alpha$ line. Differences in the relative strengths of the [O II] and [N II] lines in the three nebular regions are obvious.
tion are supposed to be negligible, as discussed in the previous paragraph. Flux calibration, which can affect the observed fluxes and consequently the extinction-corrected relative line intensities, was supposed to be accurate.

The [O III] λ5007 line was saturated in the long-exposure (1800 s) spectrum of the inner region, and the flux from the short-exposure (180 s) spectrum was thus used in Table 2. The He II λ6560 (4f^2P^0 → 6g^2G) line is blended with Hα. Using the theoretical line ratios of the hydrogenic ions (Storey & Hummer 1995) and the He II λ4686 line fluxes measured in our spectra, we estimated that the He II λ6560 line contributes ~3% and 6% to the total flux of Hα in the inner and outer region of Hu 1-2, respectively. As a consequence, the corrected fluxes of Hα will result in an increase in c(Hβ) by ~9% and 14% in the two regions. That will cause negligible changes in the extinction-corrected line intensities, given that the extinction in Hu 1-2 is low and that the inner-region extinction was adopted for the whole nebula.

The electron temperatures and densities derived for the inner and outer regions using the detected emission lines are presented in Table 3. The [O III] nebular-to-auroral line ratio yielded a temperature of 16 800 K for the inner region, and 15 200 K for the outer region. The [N ii] line ratio yielded a temperature of ~13 000 K in the inner region, but the temperature-sensitive λ5755 auroral line was not detected in the outer region. We adopted the two temperatures for the high- and low-excitation regions in Hu 1-2. An averaged electron density of 5700 cm\(^{-3}\) in the inner region was derived from the [S ii] λ6716/λ6731 and [Cl ii] λ5517/λ5537 line ratios. It agrees with the density 5770 cm\(^{-3}\) in the outer region, as derived by the [S ii] lines (Table 3). The [Cl iii] lines were not detected in the outer region.

4.2 Chemical abundances

4.2.1 Ionic abundances

Using the electron temperatures defined for the high- and low-excitation zones, we derived the ionic abundances of helium and heavy elements presented in Table 3. The He I effective recombination coefficients used for abundance determination were adopted from Benjamin, Skillman & Smits (1999). For the inner region, we adopted the He\(^{2+}/H^+\) abundance ratio derived from the λ5876 line which is the strongest He I line. For the outer region, the He\(^{2+}/H^+\) abundance derived from the λ7065 line was adopted. No He I lines were detected in the spectrum of the NW knot.

The He\(^{2+}/H^+\) abundance was derived from the He II λ4686 line, which is very strong in all the three regions of Hu 1-2 (Figure 7). The extinction-corrected flux of the He II λ4686 line in the outer region is even higher than that of the H\(^\beta\) line by ~25%, in consistency with the low intensities of the [N II] and [O II] nebular lines. Note, however, that the relative strengths of the [O II] λ3727 (a blend of the λ3726, 3729 doublet), [N II] λλ6548, 6583, and He II λ4686 lines in the NW knot are higher than those in the inner and outer regions (Table 2). The He/H ratio in the inner region (0.144) is slightly lower than that in the outer region (0.159), but a little higher than the NW knot, where no He I line was detected. The absence of He I lines in the NW knot probably indicates that helium in the NW knot is all doubly ionized, although the relatively low S/N’s of the spectrum in this region may hinder the detection of the He I lines. Given that measurements of the He I λ7065 line in the outer region of Hu 1-2 have relatively large uncertainties, the He/H abundance in the outer region is considered to agree with that in the inner region within the errors.

The N\(^{+}/H^+\) abundance derived from the [N ii] λ6583 line was adopted for the three regions because measurements of the relatively weaker λ6548 line were much affected by the nearby H\(^\alpha\) line. The Ne\(^{2+}/H^+\) abundances derived from the [Ne iii] λ3869 line were adopted because the [Ne iii] λ3967 line was blended with the H I λ3970 line. The [S ii] λ16312 line was observed in the inner and outer regions. It was blended with the He II λ6311 (5g^2G – 16f^2H^+) line, whose flux contribution was estimated from the observed λ4686 line using the hydrogenic atomic model of Storey & Hummer (1995). The corrected flux of the [S ii] λ16312 line was used to derive S\(^{2+}/H^+\). The Ar\(^{2+}/H^+\) ratio derived from the [Ar iv] λ4740 line was adopted for Hu 1-2, as the λ4711 line was blended with [Ne iv] lines.

The abundance errors following the ionic abundance ratios in Table 4 were mainly propagated from the measurement errors of the extinction-corrected relative line intensities given in Table 2. Both the [O III] λ4363 and the [N II] λ5755 temperature-sensitive auroral lines were well detected in the inner region of Hu 1-2, and the electron temperatures derived from these ions were adopted for all the three regions when calculating ionic abundance ratios (Table 4). Thus the errors in the electron temperature were small (Table 3) and not considered in the ionic abundance calculations.

4.2.2 Elemental abundances

The elemental abundances of He, N, O, Ne, S, and Ar in Table 5 were calculated using the ionization correction factor (ICF) method of Kingsburgh & Barlow (1994). No elemental abundances were calculated for the NW knot because the He I line needed for ICF calculations was not detected in this region. The He/H abundance in the inner region of Hu 1-2 derived in this paper is ~10% higher than that derived by Pottasch et al. (2003) and Hyung, Pottasch & Feibelman (2004), but it agrees with that of Peimbert & Torres-Peimbert (1987) and Peimbert, Luridiana & Torres-Peimbert (1995) within the errors. Meanwhile, the nitrogen abundance derived for the inner region by us is ~50% higher than that of the outer region, and both are lower than that of previous observations. The oxygen, neon and sulfur abundances in this paper generally agree with those of Pottasch et al. (2003) and Hyung, Pottasch & Feibelman (2004), while our argon abundance is slightly lower. However, uncertainties in abundances were not indicated in the two previous studies. We also notice that the inner-region abundances of N, O, and Ne are higher than those in the outer region.

Errors in the brackets following the total elemental abundances in Table 5 (the first two columns) were estimated mainly based on the errors in the ionic abundances through a simple propagation paradigm. For helium, the error is contributed by uncertainties in the He\(^{2+}/H^+\) and He\(^{3+}/H^+\) ratios. For heavy elements, the errors can also be introduced by the use of ICFs. This source of error is negligible for oxygen, whose ICF is always close to unity. For other heavy elements, uncertainties introduced by ICFs could be significant. The nitrogen and neon abundances were derived based on the ionic and elemental abundances of oxygen, and thus are reliable. The total sulfur abundance is generally quite uncertain, as usually only the [S ii] lines are well observed for this element. Although the [S ii] λ16312 line was also detected in the spectrum of Hu 1-2 (Table 2), it arises from an auroral transition (3p^2P^1_D – 3p^3S_0), hence it is particularly temperature sensitive. Besides, the [S iii] λ16312 line is also blended with the He II λ6311 (5g^2G – 16f^2H^+) line. Uncertainties and systematic errors in the ICFs are...
Table 3. Electron density and temperature of Hu 1-2.

|            | Inner region | Outer region |
|------------|--------------|--------------|
| \( T_e \)  | \( 16000 \pm 250 \) | \( 15 200 \pm 400 \) |
| [O iii]    | \( 13000 \pm 400 \) | \( 13000 \pm 400 \) |
| [N ii]     | \( 5100 \pm 1300 \) | \( 5770 \pm 2200 \) |
| [S ii]     | \( 6400 \pm 2800 \) | \( 6400 \pm 2800 \) |
| [Ar iv]    | \( 3900 \pm 1600 \) | \( 3200 \pm 2500 \) |

4.3 Could Hu 1-2 be a halo PN?

The abundances of the heavy elements of Hu 1-2 are generally consistent with those of the halo PNe, given their comparatively large abundance scatter as opposed to the disc PNe (Howard, Henry & McCartney 1997). Note, however, that the helium abundances of Hu 1-2 are slightly higher than those of the sample of halo PNe studied by Howard, Henry & McCartney (1997). It is thus pertinent to question whether Hu 1-2 is a halo PN or not.

Halo PNe are characterized by their height above the Galactic plane, their kinematic characteristics, and/or their low metallicity relative to disc PNe. Specifically Peimbert (1990) proposed \(|z| > 0.8 \) kpc, \( \upsilon_{pec} > 60 \) km s\(^{-1}\), and \( \log(O/H)+12 < 8.1 \) as the criteria for halo PNe, where \( z \) is the distance to the Galactic plane and \( \upsilon_{pec} \) is the peculiar radial velocity, which is the difference between the observed systemic radial velocity of a PN and its circular radial velocity \( (\upsilon_{pec} = \upsilon_{sys} - \upsilon_{circ}) \).

Peimbert & Torres-Peimbert (1983) classified Hu 1-2 as Type I PN. However, the 

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cular radial velocity \( (\upsilon_{pec} = \upsilon_{sys} - \upsilon_{circ}) \). Peña, Rechy-García & García-Rojas (2013). For Hu 1-2, at a Galactic latitude of \(-8.7^\circ\), its distance of 3.5\(\pm 0.3 \) kpc (Miranda et al. 2012a) implies a height of 0.55\(\pm 0.13 \) kpc over the Galactic plane. Its oxygen abundance is \( \log(O/H)+12 \approx 8.1 \) (see Table 5). Therefore, the oxygen abundance and its distance to the Galactic plane marginally support a halo nature. However, following the formulation by Peña, Rechy-García & García-Rojas (2013) Equation 1 therein), assuming a galactocentric distance of 8.3 kpc for the Sun, adopting a distance of 3.5\(\pm 0.3 \) kpc to Hu 1-2, and taking into account the systemic velocity of \(-3.3 \pm 1.7 \) km s\(^{-1}\) (see Section 3.2), we obtain a peculiar velocity of 22\(\pm 6 \) km s\(^{-1}\), which is much lower than required for a PN to belong to the halo. From these results we conclude that most probably Hu 1-2 is not a halo PN.
of the NW knot is characterized by lines of intermediate-to-high excitation. Besides the Hβ line, the NW knot is characterized by lines of intermediate-to-high excitation. The intensities of the [O II] λ6548, 6583 and [S II] λ6716, 6731 emission lines relative to Hβ are much stronger in the NW knot than in the inner and outer regions.

Figure 10 shows the observed line ratios in different regions of Hu 1-2 compared to those measured in the rims/shells and low-ionization structures of a sample of PNe using a set of diagnostic diagrams adopted from Raga et al. (2008). In these diagrams,
the data points associated to the rims and shells of PNe trace the locus of photoionized gas. The data points corresponding to low-ionization structures have been split into two different groups. The first one includes low-ionization structures that are projected inside the nebular shells (e.g., the bow-shock features of IC 4634), whereas the second group consists of those projected outside the nebular shells (e.g., the bow-shock features of IC 4634). This very simple classification is expected to assign mostly low-velocity photoionized structures to the first group, whereas the second group will be mostly populated by fast outflows, where irradiated shocks are expected to occur.

In the [S II]/Hα and [N II]/Hα versus [O III]/Hα diagrams, the data points of Hu 1-2 are located in the regions occupied by other PNe (Figure 10). In particular, the emission line ratios for the NW knot are compatible with those of the low-ionization structures in other PNe, with the [S II]/Hα and [N II]/Hα ratios consistently higher (by definition) than those derived for the photoionized rims and shells of PNe. Furthermore, the [O III]/Hα ratios of outflows tend to be higher than those of low-ionization structures projected inside the nebular shells. This can be evidence of an additional source of excitation, i.e., the shocks, particularly at larger distances from the central source, where the ionizing flux of photons is reduced and thus lower [O III]/Hα ratios would have been expected instead. It is also interesting to note that the NW knot of Hu 1-2 shows higher [O II]/[O III] and He II/Hα ratios than those typically seen in the low-ionization structures and outflows of other PNe. The He II/Hα ratios in the NW knot is also compatible with that observed in the inner region of Hu 1-2 (Figure 10 bottom right).

These patterns observed in Hu 1-2 might be a consequence of the very high temperature of its central star (125,000 K; Hyung, Pottasch & Feibelman 2004). The NW knot of Hu 1-2 probably harbors a significant amount of high-excitation material, and its relative amount of the high- to low-excitation material could be higher than that in the outflows and low-ionization structures of other PNe, making it a very peculiar structure.

The observed line ratios in the NW knot of Hu 1-2 are also compared in Figure 11 with the predictions for shocked regions in high-velocity knots of PNe developed by Raga et al. 2008. This comparison helps to diagnose the excitation mechanisms (photoionization, shocks, or both) in the NW knot. These models assume a cloudlet traveling away from a photoionizing source into a uniform medium ($\sim$10$^2$ cm$^{-3}$). The simulations include transfer of the ionizing radiation and a non-equilibrium ionization network of many ionic species. In Figure 11 We present the predicted line ratios from an "ad hoc" model for Hu 1-2 where a high-density ($\sim$10$^4$ cm$^{-3}$), high-velocity ($v_c = 100, 150$ and $250$ km s$^{-1}$) cloudlet with the chemical abundances measured in Hu 1-2 is moving away from a 100,000-K central star. Cases with different distances from the central source (3×10$^{17}$, 7×10$^{17}$ and 3×10$^{18}$ cm) have been simulated. Those are axisymmetric simulations, and the initial temperature of the clump/cloudlet was set to be 10$^4$ K. In order to compare the observations and the numerical simulations, we integrated the computed emission line coefficients over the entire emitting volume to derive the emission line luminosities of the NW knot of Hu 1-2. Predicted line ratios for different integration times since the start of the shock are summarized in Table 6.

The predicted [S II]/Hα, [N II]/Hα, [O I]/[O III] and He II/Hα line ratios in Table 6 show a large scatter, but they are generally comparable to those derived from the observations of Hu 1-2. The plots in Figure 11 show that the best models to reproduce the observed line ratios in the NW knot of Hu 1-2 are those for a knot at distances of a few times 10$^{17}$ cm. Models at the largest distance, 3×10$^{18}$ cm, generally predict too low [O III]/Hα ratios, which can be explained by the greater dilution of the ionizing flux from the central star. For models where the knot has smaller distances ($\sim$10$^{17}$ cm) from the central source (this is equivalent to changes in the ionizing flux at the clump), all predicted line ratios agree with those observed in the NW knot of Hu 1-2 within a factor of 2 to 3. Given the simplicity and limitations of our models (a spherical clump moving away from the central source through a constant medium, where the absorption of the photons by nebular gas between the star and the clump is not accounted for), the discrepancies between the observed line ratios and those predicted can be considered to be reasonable.

The plots in Figure 11 also help to constrain the knot velocity. Models at low velocity (100 km s$^{-1}$) tend to predict [S II]/Hα, [N II]/Hα, and [O I]/[O III] line ratios lower than those observed in Hu 1-2. On the contrary, models at high velocity (250 km s$^{-1}$) predict too high values for these line ratios. Therefore, the knot velocity seems constrained in the range 100–250 km s$^{-1}$. We note that this knot velocity is smaller than the outflow velocity >340 km s$^{-1}$ derived from a spatio-kinematical model of the outflow (Miranda et al. 2012a).

Finally, we remark the persistent difficulty of our models to reproduce the observed [O III]/Hα line ratios. This issue can be alleviated by increasing the oxygen abundance assumed by our model. We tested this by increasing the oxygen abundance, and found that increasing the abundance within the uncertainty of our abundance determination produced some improvement (not shown in Figure 11); however it was insufficient to reproduce the observed [O III]/Hα line ratio.

4.5 The jet-launching engine of Hu 1-2

The total mass, momentum and mechanical luminosity of the jets can be used to assess the jet-launching engine of a PN or proto-PN (e.g., Bujarrabal et al. 2001, Blackman & Lucchini 2014). Similar diagnosis is carried out for Hu 1-2 below. The ionized mass of the NW knot can be estimated from its Hβ flux. Using the total Hα flux of the NW knot derived from the NOT Hα flux-calibrated image presented in Figure 1 and the Hα to Hβ ratio derived 1-D spectrum in Table 2, we derived a total Hβ flux of $\sim$3×10$^{-15}$ erg cm$^{-2}$ s$^{-1}$ for the NW knot. Adopting a distance of 3.5 kpc (Miranda et al. 2012a), and an angular radius of 2"., an electron temperature of 10$^5$ K, and a filling factor of 0.4, we estimated an electron den-
Table 6. Shock model results compared with observations of the Hu 1-2 NW knot.

| $v_c$ (km s\(^{-1}\)) | Distance ($\times 10^{18}$ cm) | $t$ (years) | [O ii]/H\(\alpha\) | [O iii]/H\(\alpha\) | [N ii]/H\(\alpha\) | [S ii]/H\(\alpha\) | He ii/H\(\alpha\) |
|------------------------|-------------------------------|---------------|------------------|------------------|--------------------|-----------------|---------------|
| 100                    | 0.3                           | 50            | 0.280            | 1.000            | 0.340              | 0.028           | 0.380         |
|                        |                               | 200           | 0.388            | 1.220            | 0.582              | 0.046           | 0.347         |
|                        |                               | 350           | 0.118            | 1.580            | 0.145              | 0.018           | 0.421         |
| 100                    | 0.7                           | 50            | 0.468            | 0.915            | 0.839              | 0.120           | 0.176         |
|                        |                               | 200           | 0.515            | 1.410            | 0.938              | 0.188           | 0.181         |
|                        |                               | 350           | 0.482            | 1.870            | 0.802              | 0.129           | 0.193         |
| 100                    | 3.0                           | 50            | 0.519            | 0.094            | 1.090              | 0.393           | 0.111         |
|                        |                               | 200           | 0.659            | 0.048            | 1.680              | 0.553           | 0.578         |
|                        |                               | 350           | 0.826            | 0.060            | 2.070              | 0.554           | 0.022         |
| 150                    | 0.3                           | 50            | 0.588            | 0.882            | 0.916              | 0.062           | 0.313         |
|                        |                               | 200           | 0.566            | 1.000            | 0.981              | 0.138           | 0.302         |
|                        |                               | 350           | 0.384            | 1.400            | 0.622              | 0.085           | 0.343         |
| 150                    | 0.7                           | 50            | 0.588            | 0.882            | 0.951              | 0.196           | 0.164         |
|                        |                               | 200           | 0.501            | 1.470            | 0.894              | 0.249           | 0.185         |
|                        |                               | 350           | 0.439            | 1.920            | 0.705              | 0.179           | 0.200         |
| 150                    | 3.0                           | 50            | 0.684            | 0.130            | 1.120              | 0.468           | 0.233         |
|                        |                               | 200           | 0.704            | 0.048            | 1.690              | 0.592           | 0.352         |
|                        |                               | 350           | 0.835            | 0.060            | 2.040              | 0.597           | 0.429         |
| 250                    | 0.3                           | 40            | 0.838            | 0.666            | 1.486              | 0.132           | 0.250         |
|                        |                               | 120           | 0.503            | 0.847            | 0.759              | 0.425           | 0.306         |
|                        |                               | 200           | 0.401            | 1.276            | 0.606              | 0.278           | 0.346         |
| 250                    | 0.7                           | 40            | 0.815            | 0.775            | 1.025              | 0.283           | 0.146         |
|                        |                               | 120           | 0.500            | 1.606            | 0.568              | 0.525           | 0.173         |
|                        |                               | 200           | 0.477            | 2.047            | 0.600              | 0.352           | 0.188         |
| 250                    | 3.0                           | 40            | 0.943            | 0.217            | 1.132              | 0.535           | 0.017         |
|                        |                               | 120           | 1.026            | 0.173            | 1.679              | 0.826           | 0.021         |
|                        |                               | 200           | 0.946            | 1.056            | 1.925              | 0.683           | 0.020         |
| Observations\(^a\)    |                               |               | 1.415            | 2.735            | 0.920              | 0.080           | 0.368         |

\(^a\) Observations of the NW knot of Hu 1-2.

The study of $\sim 200$ cm\(^{-3}\) and an ionized mass of $\sim 2 \times 10^{-5} M_\odot$ for the bipolar knots of Hu 1-2.

The dynamical age of the bipolar knots of Hu 1-2 is well constrained to be 1375 yr under the assumption that the knots have been moving ballistically since their ejection (Miranda et al. 2012\(^a\)). Under the same assumption, the ejection time-scale of these knots can be estimated from the ratio between their angular size, $\sim 4''$, and their distance to the central star, $\sim 27''$. This result in an ejection time-scale ($\tau_{\text{jet}}$) $\sim 200$ yr. The averaged mass-loss rate during the ejection would then be $\sim 1 \times 10^{-7} M_\odot$ yr\(^{-1}\).

The mechanical luminosity of the jets can be estimated using the equation

$$L_{\text{mec}} = \frac{1}{2} M_{\text{knot}} v_{\text{exp}}^2 \frac{\tau_{\text{jet}}}{\tau_{\text{jet}}} \tag{3}$$

where $M_{\text{knot}}$ is the total ionized mass of the knots, $v_{\text{exp}}$ is the expansion velocity (340 km s\(^{-1}\); Miranda et al. 2012\(^a\)), and $\tau_{\text{jet}}$ is the jet ejection time-scale ($\sim 200$ yr). Thus the jets mechanical luminosity of Hu 1-2 would be $\sim 0.5 L_\odot$. The total energy of the jets is $\sim 1.2 \times 10^{43}$ erg, which is lower than the kinetic energies of fast outflows in proto-PNe (e.g., the sample studied by Bujarrabal et al. 2001) by at least one order of magnitude. The momentum estimated for the bipolar knots of Hu 1-2 is $\sim 1.4 \times 10^{36}$ g cm s\(^{-1}\), also much lower than those ($10^{37}$–$10^{40}$ g cm s\(^{-1}\)) observed in proto-PNe, whose high linear momenta defy any easy interpretation (Bujarrabal et al. 2001).

The parameters associated to the jet launching in Hu 1-2 and those studied by Tocknell, De Marco & Wardle (2014) are presented in Table 7. A comparison among them indicates that the bipolar knots of Hu 1-2 are lighter, less massive than those of the Necklacen.\(^a\) The parameters associated to the jet launching in Hu 1-2 and those studied by Tocknell, De Marco & Wardle (2014) are presented in Table 7. A comparison among them indicates that the bipolar knots of Hu 1-2 are lighter, less massive than those of the Necklacen.\(^a\)

Table 7. Physical properties of collimated outflows in PNe.

| PN                | $M_{\text{knot}}$ ($M_\odot$) | $v_{\text{exp}}$ (km s\(^{-1}\)) | $\tau_{\text{jet}}$ (yr) | $L_{\text{mec}}$ (L\(\odot\)) |
|-------------------|-------------------------------|---------------------------------|--------------------------|-------------------------------|
| Hu 1-2            | $\sim 2 \times 10^{-5}$       | 340                             | 200                      | 0.5                           |
| The Necklace\(^a\)| $\sim 10^{-3}$                | 95(N), 115(S)                   | 3700–8000                | 0.1–0.23                     |
| NGC 6778\(^a\)   | $1.5 \times 10^{-3}$         | 270                             | 460                      | 1700                          | 5.3

\(^a\) From Tocknell, De Marco & Wardle (2014).
Necklace Nebula and NGC 6778, whereas their ejection time-scale is much shorter. The two effects combined result in very similar mechanical luminosities for all sources in Table 7. We note the large uncertainty in the estimate of the ejection time-scale of the knots of Hu 1-2. Dynamical effects are certainly playing a crucial role in the evolution of the outflow, compressing the head of the flow (reducing the apparent ejection time-scale) or lagging material upstream (increasing the apparent ejection time-scale). Thus this ejection time-scale could be quite uncertain and so is the derived jets mechanical luminosity ($L_{\text{mech}}$) of Hu 1-2.

It is interesting to note that the jets mechanical luminosity of NGC 6778 is extremely high (Table 7), if we adopt the parameters given in Tocknell, De Marco & Wardle (2014). This PN, which has a similar distance (~2.6 kpc; Tocknell, De Marco & Wardle 2014) as Hu 1-2, has a highly disrupted equatorial ring and a binary central star (Miszalski et al. 2011b; Guerrero & Miranda 2012). Both NGC 6778 and the Necklace Nebula in Table 7 have a post-common envelope (post-CE) close binary in the center (Miszalski et al. 2011b; Corradi et al. 2011). Like NGC 6778, Hu 1-2 displays an overall bipolar structure and a likely disrupted equatorial ring. This resemblance suggests that Hu 1-2 might have similar jet-launching mechanisms as the other two PNe.

5 CONCLUSIONS

We have presented a thorough imaging and spectroscopic study of the main nebular regions and bipolar outflows of Hu 1-2. The physical structure of the main nebula can be described as bipolar, although its velocity field cannot be described by a simple hour-glass law. The inclination of the bipolar lobes is $\leq 10^\circ$ and its polar expansion velocity $\approx 150$ km s$^{-1}$, resulting in a lower-limit expansion age $\lesssim 1100$ yr. Neither the morphology nor the kinematics of the central, $z$-shaped innermost region of Hu 1-2 can be simply described as a waist or torus located between the two bipolar lobes. The knotty morphology of this region and its relatively high expansion velocity, $\approx 40$ km s$^{-1}$, are suggestive of a “broken” equatorial ring. The distorted velocity field of the bipolar lobes and the complex morphology of the equatorial regions make us conclude that Hu 1-2 has experienced notable violent dynamical processes during its formation. Similar interpretation has been given to the disrupted equatorial regions of a few bipolar PNe known to harbor binary systems (e.g., NGC 6778, NGC 7354; Contreras et al. 2010; Miszalski et al. 2011b; Guerrero & Miranda 2012). It is tempting to conclude that the fast bipolar knots present in all these sources are dynamical agents which caused the disrupted equatorial features.

It is interesting to remark here the apparent discrepancies implied by the chemical abundances of Hu 1-2. The high He/H and N/O abundance ratios suggest a Type I nature for Hu 1-2, which indicates that it descended from a relatively massive intermediate-mass progenitor star ($\gtrsim 4 M_\odot$; e.g., Karakas et al. 2009). On the other hand, the low abundances of the heavy elements of Hu 1-2 suggest it formed long time ago, probably in an early-stage of the chemical evolution of the Galaxy, and thus it corresponds to a low-mass progenitor. Cases of Type I PNe with very low abundances of $\alpha$ elements can be interpreted as a result of formation of a massive PN progenitor from unmixed (i.e., metal-poor) interstellar material (Milingo et al. 2010). Therefore, the chemical composition of Hu 1-2 probably does not represent that of its current environment. This might indeed be the case. At a galactocentric distance $\sim 9$ kpc, as estimated from the distance to Hu 1-2 ($\sim 3.5$ kpc; Miranda et al. 2012a), its Galactic longitude ($86.5^\circ$) and the galactocentric distance of the Sun (8.3 kpc; Gillessen et al. 2009), the oxygen abundance of the interstellar medium is $\sim 4 \times 10^{-4}$ (Henry et al. 2010 and Figure 1 therein), which is much higher than that of Hu 1-2 (see Table 5). Alternatively, Type I PNe have long been con-
Figure 10. Diagnostic diagrams of several emission line ratios for rims/shells (open circles), low-ionization structures projected onto the nebular shells (stars), and outflows (filled circles) for a sample of PNe: ETHOS 1, He 1-1, IC 4634, K 1-2, KjPn 8, NGC 6543, NGC 6826, NGC 7009, NGC 7354, and NGC 7662 (Balick et al. [1994] Conreras et al. [2010] Exter, Pollacco & Bell [2003] Gonçalves et al. [2003, 2009] Guerrero et al. [2008] López-Martín et al. [2002] Miszalski et al. [2011a]). The emission line ratios for Hu 1-2 are shown in red.

...connected to bipolar morphology (e.g., Peimbert & Torres-Peimbert [1983] which is likely the result of binary interactions (e.g., Soker [1997]) or common envelope binary interaction (e.g., Zijlstra [2007] De Marco [2009] Miszalski et al. [2009]). The abundance pattern of Hu 1-2 might be due to the effects of binary interactions on the evolution of the progenitor and the composition of the subsequent PN, although so far it is not clear whether there is a binary central star in Hu 1-2. Detailed discussion of this point is beyond the scope of this paper. We also discussed the possibility of Hu 1-2 being a halo PN, given that it is quite out of the Galactic plane ($b = -8.8^\circ$). Although the oxygen abundances of Hu 1-2 and its distance to the Galactic plane make it seem likely to be a halo PN, its low peculiar radial velocity obviously argues against a halo nature for Hu 1-2.

The collimated bipolar outflows of Hu 1-2 are particularly interesting. They show a notable bow-shock-like morphology. The emission within these structures is found to be highly stratified, with [N II] peaking at the leading edge of the bow-shock and [O III] mostly occupying the star-facing region. This profile is similar to that found in the bow-shock structures of PNe such as IC 4634 and NGC 7009. Previous spatio-kinematical studies have suggested an expansion velocity $> 340$ km s$^{-1}$ for the outer knots of Hu 1-2. This high expansion velocity of the bipolar knots, together with the bow-shock-like morphology associated with them, indicate that the high-velocity, collimated bipolar outflows are moving through the interstellar medium like “bullets”.

The line ratios of the NW knot of Hu 1-2 and those from the collimated outflows of other PNe are generally consistent with those of other low-ionization structures, but they exhibit higher [O III]/H$\alpha$ ratios. This line ratio is particularly high in Hu 1-2, indicating that both low- and high-excitation gas are present at the location of this feature with significant amounts. The observed line ratios of the NW knot of Hu 1-2 have been modeled using “ad hoc” simulations of a fast moving cloudlet in a medium with homogeneous density. The model predictions are generally consistent with the observed line ratios, thus confirming that the excitation of the bipolar knots of Hu 1-2 can be explained by a mix of the UV radiation and shocks. The models favor distance, nebular abundances, and stellar parameters consistent with those derived for Hu 1-2. As reported for the collimated outflows of other PNe and proto-PNe (e.g., Hen 3-1475; Riera et al. [2006]), the best knot velocity...
Figure 11. Similar to Figure 10, but comparing the emission line ratios predicted for a shocked cloudlet moving away from a photoionizing source with those seen in the NW knot of Hu 1-2 (the green star) for different distances from the central star and at different expansion velocities (see description of the symbols in the upper-left panel). Symbols of the same models are connected with dotted lines to show the time-evolution sequences.
(100–250 km s$^{-1}$) inferred from the models is below that derived by spatio-kinemathical studies (>340 km s$^{-1}$).

Finally, we estimated the ionized mass of the NW knot of Hu 1-2, and calculated the jets mechanical luminosity using the knots' mass and the ejection time-scale based on the dynamical age of the bipolar outflow. The jets mechanical luminosity and the mass-loss rate of Hu 1-2 generally agree, within the uncertainties, with those of the Necklace and NGC 6778, both of which have a post-common envelope close binary central star. The resemblance of Hu 1-2 with NGC 6778 in nebular structure and morphology hints at a possibility that the former might have similar jet-launching engine as the latter.

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