Revista Mexicana de Astronomía y Astrofísica, **41**, 109–119 (2005)

THE GLOBAL KINEMATICS OF THE DUMBBELL PLANETARY NEBULA (NGC 6853, M27, PN G060.8-03.6)

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Received 2004 December 2; accepted 2005 January 25

RESUMEN

Se han obtenido perfiles resueltos espacialmente de las líneas de emisión de He II 6560 Å, Hα y [N II] 6548 and 6584 Å sobre dos largos cortes ortogonales en la nebulosa planetaria conocida como *Dumbbell.* Se muestra que el volumen central brillante que emite He II 6560 Å es particularmente inerte, con velocidades de expansión ≤ 7 km s^{-1}. Esta zona está envuelta por un cascarón que emite en [O III] 5007 Å y que se expande a 13 km s^{-1} y otro cascarón externo, también de [O III] 5007 Å, expandiéndose a 31 km s^{-1}. Un siguiente cascarón externo que emite en [N II] 6584 Å, se expande a 35 km s^{-1}. Se presenta una nueva imagen de Hα + [N II] 6548 and 6584 Å con continuo substraído, que abarca el halo de 15$'$ de diámetro y se compara con medidas recientes de movimientos propios de la estrella central y con perfiles de líneas de emisión de la sección interior del halo, presentados aquí. Estos datos suguieren interacción de la nebulosa con el medio ambiente interestelar. El cascarón brillante que emite en [N II] 6584 Å debe estar penetrando el halo, que es relativamente inerte, con una velocidad diferencial ≥ 25 km s^{-1}. Los resultados aquí presentados se comparan con modelos actuales para la creación de nebulosas planetarias.

ABSTRACT

Spatially resolved profiles of the He II 6560 Å, Hα and [N II] 6548 and 6584 Å nebular emission lines have been obtained in two orthogonal long cuts over the Dumbbell planetary nebula. The central He II 6560 Å emitting volume of the bright dumbbell structure is shown to be particularly inert with an expansion velocity of ≤ 7 km s^{-1}. This is enveloped by an inner [O III] 5007 Å emitting shell expanding at 13 km s^{-1}, an outer [O III] 5007 Å shell expanding at 31 km s^{-1} which is on the inside of the outer [N II] 6584 Å emitting shell expanding at 35 km s^{-1}. A new Hα + [N II] 6548 and 6584 Å continuum-subtracted image of the 15$'$ diameter halo has also been compared with recent proper motion measurements of the central star and the present line profiles from the halo's inner edge. Interaction with the ambient interstellar medium is suggested. The bright [N II] 6584 Å emitting shell must be running into this relatively inert halo with a differential velocity of ≥ 25 km s^{-1}. The present results are compared with currents models for the creation of planetary nebulae.

Key Words: **PLANETARY NEBULAE: INDIVIDUAL: DUMBBELL, NGC 6853 — ISM: KINEMATICS AND DYNAMICS**

1. INTRODUCTION

NGC 6853 (M27, PN G060.8–03.6) is a planetary nebula (PN) of large angular size, more commonly known as the Dumbbell Nebula. Its distance has been measured by parallax observations as 360 ± 60 pc (Pier et al. 1993; Harris et al. 1997) and 420±60 pc (Benedict et al. 2003), making it one of the closest PNe.

This object has been classified morphologically by Balick (1987) as late elliptical, by Chu, Jacoby, & Arendt (1987) as a Type I multiple shell planetary

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nebula, and by Manchado et al. (1996) as elliptical with inner structure and multiple shells.

The elliptical main body of the nebula has an angular size of $8' \times 5'$ along the major and minor axes at position angles (PA) 125° and 35° respectively, with the maxima of brightness at the ends of the minor axis (the bar-like feature which crosses the nebula from NE to SW).

The main nebula was reported to contain a so-called second internal shell (Maury & Acker 1990) of angular dimensions $1.'2 \times 0.'8$, visible in the UV (Maury & Acker 1990) and in the [S II] 6717 and 6731 Å emission lines (Moreno-Corral, López-Molina, & Vázquez 1992). Also it is surrounded by an extended (15 arcmin across) fainter halo first reported by Millikan (1974). Balick et al. (1992), Moreno-Corral et al. (1992), and Papamastorakis, Xilouris, & Paleologou (1993) have all presented narrow band images of the Dumbbell showing this extensive halo and noted the existence of radial 'rays' connecting the halo and the main nebula. The recent deep images of Manchado et al. (1996) show all these features very clearly.

The central star of Dumbbell nebula is classified as O7 (Cerruti-Sola & Perinotto 1985) and its estimated temperature and luminosity are characteristic of an evolved planetary nebula nucleus. Absolute parallax and relative proper motion for this star have recently been presented by Benedict et al. (2003). The central star is also responsible for the reported X-ray emission of the nebula (Chu, Kwitter, & Kaler 1993) for its surface temperature is $\approx 10^5$ K (Napiwotzki 1999).

Zuckerman & Gatley (1988) mapped the molecular hydrogen emission and found that it followed the brightest regions of optical emission. Huggins et al. (1996) have detected CO emission and find a complex filamentary structure to the molecular gas. Spectral observations at a point 68″ S, 63″ W of the central star (coinciding with the brightest optical emission) show line splitting of 30 km s^{-1}. Kastner et al. (1996) present a detailed H_2 map again showing the complex structure of the neutral gas. Dusty globules of molecular gas in the near side of the outer [N II] 6584 Å and [O I] 6300 Å emitting shell of the central bar of the nebula were discovered by Meaburn & López (1993), silhouetted against the more central [O III] 5007 Å and He II 4686 Å emission, suggesting that they have been ejected in the post-asymptotic phase of the central star.

Goudis et al. (1978) obtained insect-eye Fabry-Perot interferograms of the [O I] 6300 Å, [O III] 5007 Å and [N II] 6584 Å emission lines from the Dumbbell. They found that the lower excitation [O I] 6300 Å and [N II] 6584 Å emission could be explained by a cylindrical structure, expanding radially with respect to its axis with an expansion velocity of ~ 30 km s^{-1}, although they note that the [O III] 5007 Å emission from near the exciting star indicates more complex motions. More recent observations of the [O III] 5007 Å emission (Meaburn, Christopoulou, & Goudis 1992) obtained from the very central region of the Dumbbell revealed the presence of four distinct velocity components within each emission line profile, indicating the existence of an outer shell expanding at 31 km s^{-1} (probably connected to the low-ionisation structure) and the suggestion of an inner shell expanding radially at 12 km s^{-1}(Meaburn et al. 1992). Such a double-shell structure in the light of [O III] 5007 Å has also been observed in the Helix nebula (Meaburn et al. 1998, O'Dell, McCullough, & Meixner 2004).

In the present paper, longslit spectroscopic observations of the Dumbbell nebula obtained with high spectral and spatial resolution, across both the main nebular shell and fainter halo, are presented. A new deep wide-field image, with continuum subtracted, permits comparison with both the kinematical features of the halo that are presented here and a recent proper motion measurement of the central star by Benedict (2003). The spatio-kinematical structure of the various components of the Dumbbell nebula can be compared in a significant way with the predictions of dynamical models.

2. OBSERVATIONS AND RESULTS

2.1. *Deep Imagery*

The wide-field image of Dumbbell nebula shown in Figures 1a and b, was obtained with the 0.3 m Schmidt-Cassegrain telescope at Skinakas Observatory, Crete, Greece on June 13, 2004. The observations were performed with a 1024×1024 Thomson CCD which provides a $70' \times 70'$ field of view and an image scale of 4″ per pixel. The Dumbbell nebula was observed for 4800 s in total through the Hα plus [N II] 6548 and 6584 Å filter and for 180 s with the corresponding continuum filter. The latter continuum image was subtracted from the former line emission image to eliminate the confusing star field (more details of this technique can be found in Boumis et al. 2002). The astrometric solution was made using the *HST* Guide star catalogue (Lasker, Russel, & Jenkner 1999). The equatorial coordinates quoted in this work refer to epoch 2000. Standard IRAF and MIDAS routines were employed for the reduction of the data. All frames were bias subtracted

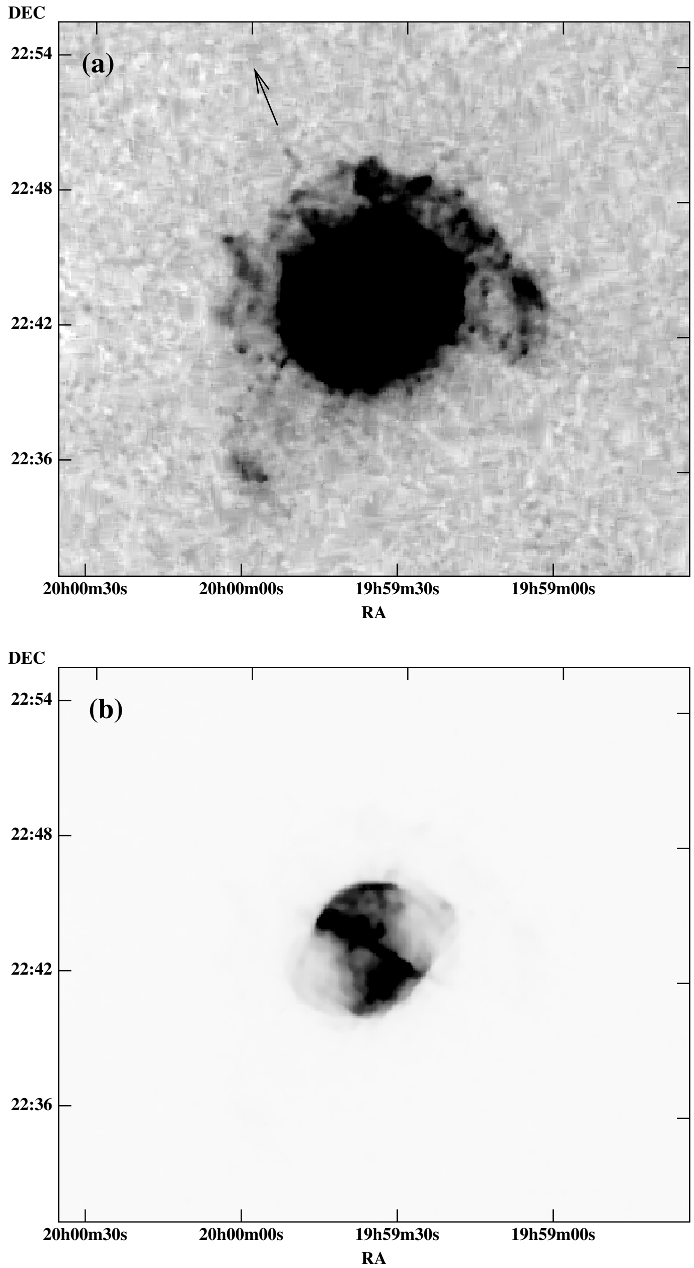

Fig. 1. (a) A deep representation of the continuum subtracted Hα plus [N II] 6548 and 6584 Å image. This is an enlargement from the whole 70′ x 70′ field.The arrowed line indicates the proper motion found for the central star. (b) A lighter representation of the same image shown in (a).

and flat-field corrected using a series of well exposed twilight flat-fields.

2.2. *Spectroscopy*

Spatially resolved profiles of the He II 6560 Å [N II] 6584 Å and Hα nebular emission lines along five slit positions were obtained on 19–21 Nov. 1987 (as yet unpublished) at high spectral resolution with the Manchester Echelle Spectrometer (MES; Meaburn et al. 1984) combined with the f/8 (converted) focus of the 4.2 m William Herschel Telescope (WHT).

MES was used in its primary mode with a narrow band 100 Å bandwidth interference filter isolating the 87$^{\rm th}$ echelle order. The IPCS-CCD detector was used with 260 increments (each of 0.″75) along the slit length (195″) and 1260 data receiving channels in the dispersion direction. The slit width was 150 μm to give a spectral resolution of 11 km s^{-1}.

Three of the slit positions were orientated along the SW-NE direction of the nebula (effective angular length on the sky $8'.4$) as marked in Figure 2 whereas the other three were employed in the NW-SE direction (angular length on the sky $8'.4$) are also marked in Fig. 2.

The resultant spectra were calibrated to ± 1 km s^{-1} accuracy against the reference spectra of a CuAr lamp. The reduction of the data was performed on the Manchester node of the UK STARLINK computer network using the FIGARO, KAPPA, CCDPACK packages. Each sequence of the separate data sets was combined into a single mosaic in each direction using the CCDPACK routine MAKEMOS in order to eliminate possible discontinuities caused by the different effective exposure times and background levels of the slits.

Greyscale representations of the final mosaics of the position – velocity (pv) arrays of profiles along the SW-NE and NW-SE directions of the nebula are presented in Figure 3 for both Hα and [N II] 6584 Å emission lines.

Profiles from the central increment (marked 0 arcmin in the NW-SE arrays in Figure 3) of the He II 6560 Å, Hα , and [N II] 6584 Å emission lines are compared in Figure 4. [N II] 6584 Å line profiles from the positions marked A-G along the NW-SE array (see Fig. 3) are shown in Fig. 5. These are for $3''$ wide lengths along the array each centred on these positions.

Deep, negative, greyscale representations of the parts of the pv arrays (He II 6560 Å, Hα and [N II] 6548 and 6584 Å) that include the faint halo of NGC 6853 are shown in Figure 6. Hα and [N II] 6584 Å line profiles for the halo emission are shown in Figure 7.

3. DISCUSSION

3.1. *New Kinematical Features*

The most striking feature of the pv arrays of profiles from the main body of NGC 6853 in Figs. 3 and 4 is that the Hα emission appears to originate within a large fraction of the nebular volume whereas [N II] 6584 Å emission comes from an outer shell expanding at 35 km s^{-1} with a systemic heliocentric radial velocity of $V_{\rm SYS} = -41$ km s^{-1}. Even though the thermal width of the Hα line at 10,000 K ($\equiv 21.4$ km s^{-1} which dominates the intrinsic broadening by the fine structural components of the Hα line —see below) is 3.7 times greater than that for [N II] 6584 Å it alone cannot explain the large differences between the [N II] 6584 Å and Hα profiles in Fig. 4. After all the [N II] 6584 Å velocity components are separated by 70 km s^{-1}. Moreover, an unpublished image of the the He II 4686 Å emission (O'Dell —private comm.) of NGC 6853 shows that it originates in a diffuse central volume, $180'' \times 160''$ in size where the long axis is aligned with the bright central bar of the nebula. This image was taken with the same system employed for NGC 7293 (O'Dell 1998). The observed width of the central He II 6560 Å profile in Fig. 4 has been measured in the present work as 29.5 ± 1.3 km s^{-1} by fitting a single Gaussian.

The He II 6560 Å line is composed of nineteen fine structural components covering the 6559.769–6560.209 Å range. The intrinsic width of the He II 6560 Å profile as a consequence can be approximated by a single Gaussian of ≥ 10 km s^{-1} width (the brightness distribution will not be the same for all components; e.g., the seven components that constitute the Hα line lie between 6562.709–6562.909 Å but can be reasonably simulated by a single Gaussian of width 0.14 Å i.e., $\equiv 6.4$ km s^{-1}). When the intrinsic width of the He II 6560 Å line is combined with an 11 km s^{-1} wide instrumental profile and a 10.7 km s^{-1} thermal width (at 10,000 K) this leaves the turbulent motions combined with any global expansion of the He II 6560 Å volume to contribute only ≤ 12 km s^{-1} to the observed width of the central line profile. If turbulent motions within this central volume are around the sound speed (say 10 km s^{-1}) then any radial expansion of the central He II 6560 Å emitting volume must then be ≤ 7 km s^{-1}. Note that the inner [O III] 5007 Å emitting shell, whose existence is inferred by spatially limited observations, has a measured expansion velocity of only 13 km s^{-1} (Meaburn et al. 1992).

In summary, the complex Hα profile in Fig. 4 must originate in the outer [N II] 6584 Å emitting shell expanding at 35 km s^{-1}, the [O III] 5007 Å emitting shell on its inside surface expanding at 31 km s^{-1} (Meaburn et al. 1992), the inferred inner [O III] 5007 Å emitting shell expanding at 13 km s^{-1} (Meaburn et al. 1992) as well as in the inner central He II 6560 Å emitting volume whose expansion, if any exists, is shown here to be ≤ 7 km s^{-1}. The resultant broad and complex Hα profile in Fig. 4 is consequently the emission in different proportion from all of these regions along this sight line convolved with the larger thermal width of the Hα line.

Details of interest in these pv arrays are the 'V-shaped' features (two examples are arrowed in Fig. 3) about $20''$ across and extending in radial velocity beyond that of the expanding shell.

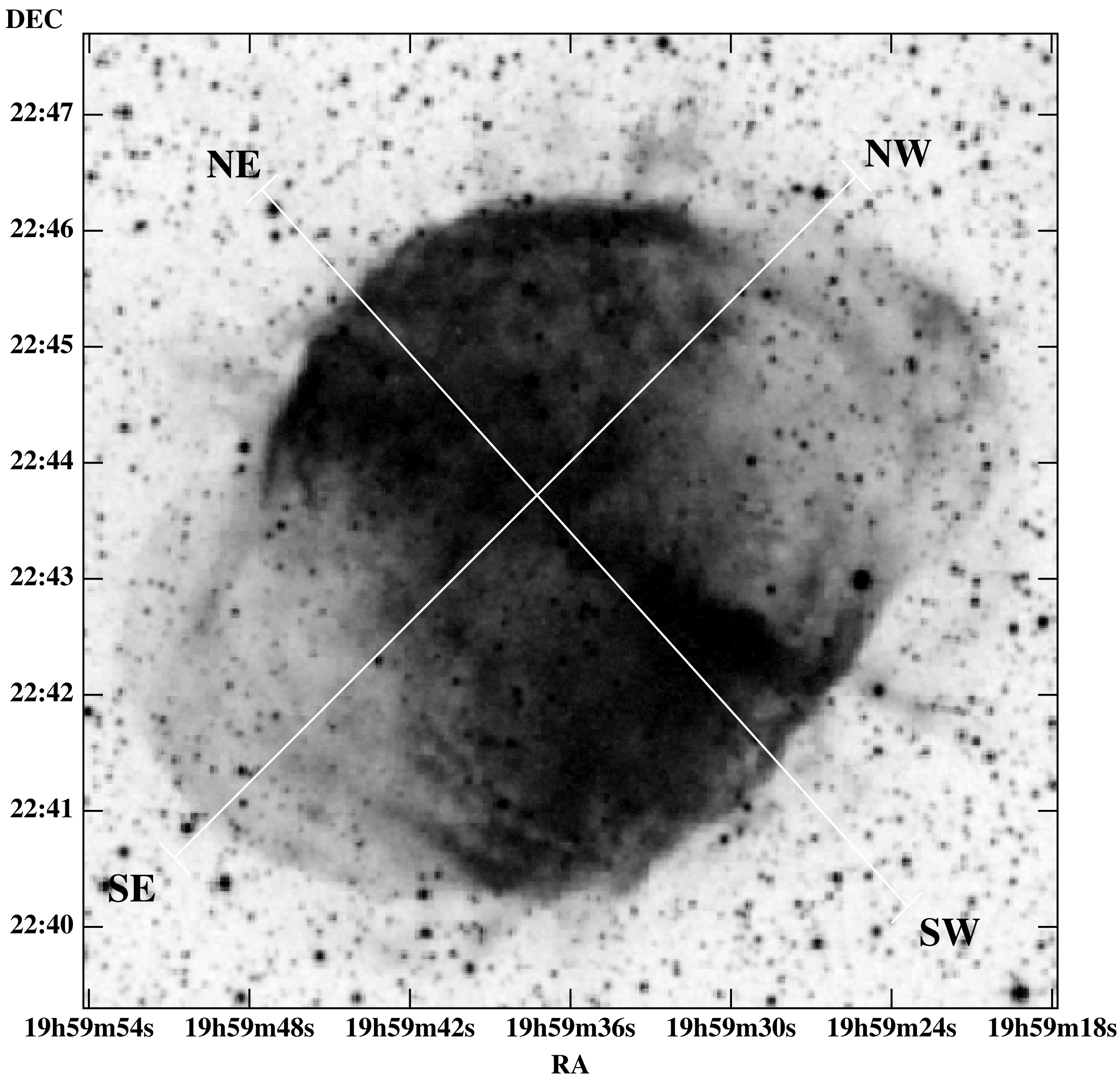

Fig. 2. The NW-SE and SW-NE slit positions where profiles were obtained, are shown against a 8.′5 × 8.′5 DSS2 Red image of the Dumbbell nebula.

The [N II] 6584 Å profiles along the SW-NE pv array describe a reasonable 'velocity ellipse' indicating circular radial expansion, whereas those along the NW-SE length are nearly open-ended. A barrel-shaped or quasi ellipsoidal, expansion is indicated.

The [N II] 6584 Å profiles from the SW end of the slit in Figs. 6 and 7 cover the inner part of the faint outer halo and exhibit (see Fig. 1) two velocity components separated by about 25 km s^{-1} centred on the nebular V_{SYS}. Perhaps more significantly those from the NE end are narrow (20 km s^{-1}) and single. Any expansion of the halo must then be ≤ 13 km s^{-1}. Within this interpretation the inner bright [N II] 6584 Å emitting shell must be running into this halo with a differential velocity of ≥ 22 km s^{-1}.

It is interesting that Benedict et al. (2003) give the proper motion of the central star as 19.2±1 mas yr^{-1} along PA 21±1° (see arrowed line in Fig. 1a) which at a distance of 420 pc. indicates a tangential velocity of 37 km s^{-1}.

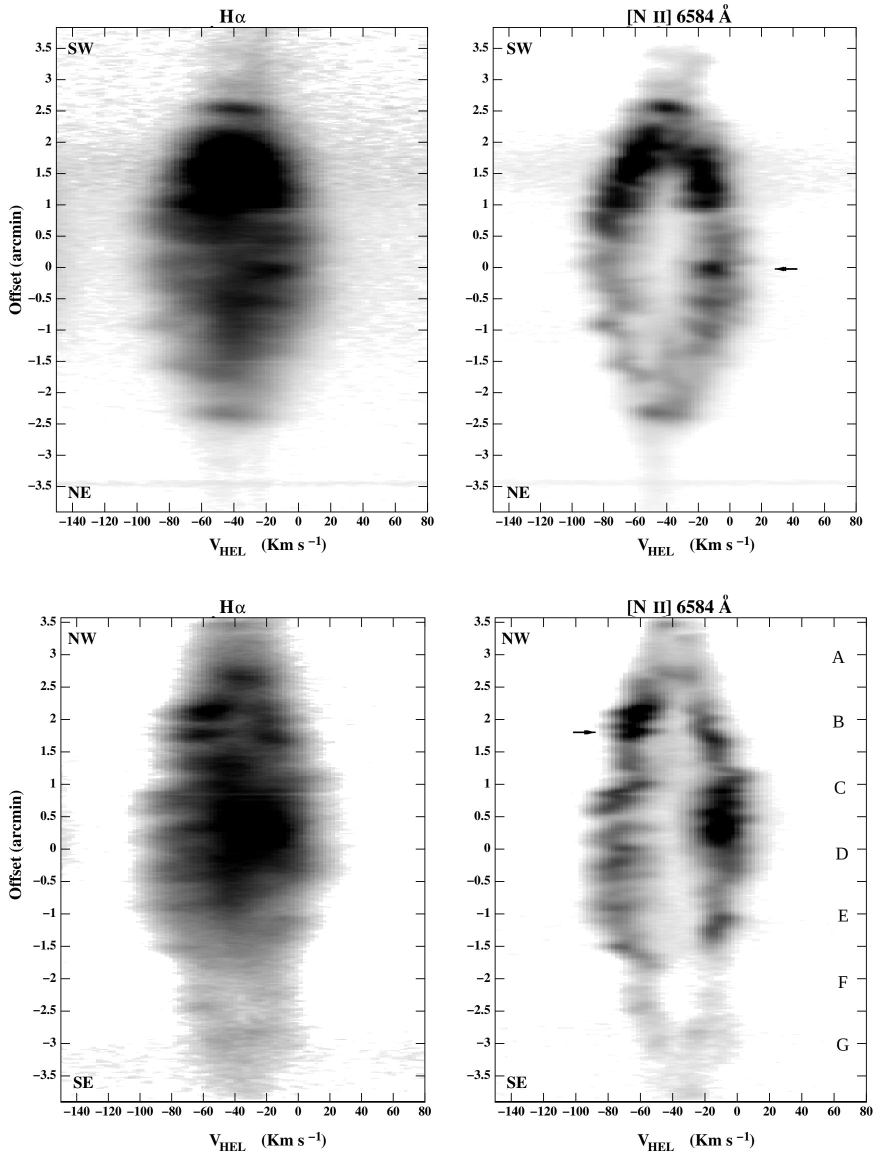

Fig. 3. Position velocity (pv) arrays of the Hα and [N II] 6584 Å profiles from the SW-NE and NW-SE slits are shown in the top and bottom images, respectively. The horizontal axes are corrected to heliocentric radial velocity ($V_{\rm HEL}$) and the vertical axes are in arcmin and correspond spatially to the solid lines in Fig. 1. Two examples of the 'V-shaped' velocity features are arrowed. The [N II] 6584 Å line profiles shown in Fig. 5 were extracted from the positions A–G (each cut 3 arcsec wide) marked against the [N II] 6584 Å greyscale for the NW-SE slit (see Fig. 2).

3.2. *Dynamics*

Planetary nebulae (PNe) are formed by mass loss from stars with initial masses <8 $M_\odot$. Since fast stellar winds with terminal velocities of 600–3500 km s^{-1} have been detected in a large number of PN nuclei and since the progenitors of PNe have lost mass via slow winds at the red giant phase and via 'superwinds' on the asymptotic giant branch (AGB) at 10–25 km s^{-1}, the fast stellar winds inevitably will catch up and interact with the previous slow winds. The standard interacting winds model (Kwok, Purton, & Fitzgerald, 1978; Khan & West 1985; Chu et al. 1993; Frank (1999); Balick & Frank 2002) has provided an elegant explanation for the formation of the nebular structure in planetary nebulae during the transition of the stellar core from the post-AGB to the white dwarf stages.

In these models the PN system consists of a central star, an energetic stellar wind, an expanding ionized shell and the remnant envelope of the

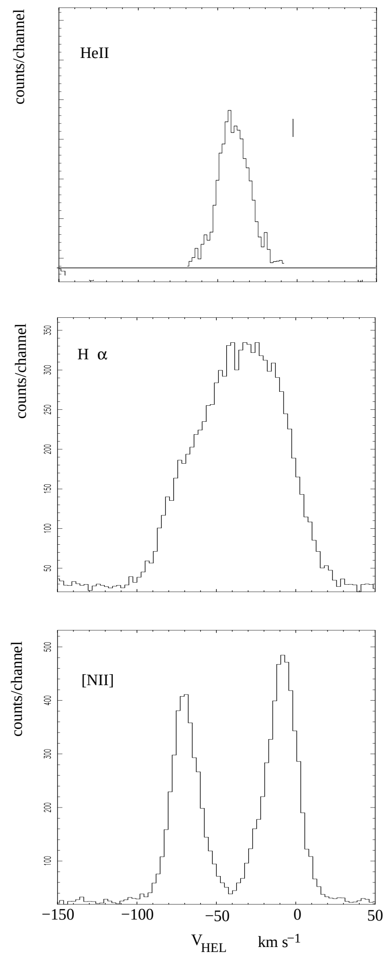

Fig. 4. Hα and [N II] 6584 Å line profiles from a 1 arcsec long increment of the slit length over the nebular core i.e., at 0′ position for the NW-SE slit in Fig. 3 are compared with the profile of the He II 6560 Å emission line but extracted, because of its faintness, for a 20″ width centred on the same position. The counts/channel for this He II 6560 Å profile are unreliable and therefore omitted but its peak surface brightness is around 0.05 that of the Hα line.

progenitor red giant. The observations show that most PNe can basically be described in terms of the above model but there are some difficulties for complex PN with multiple shell components where peculiar ejection processes, related to the evolution and/or the nature of the central star, have been invoked (Miranda & Solf 1992).

The pv arrays shown in Figs. 3 and 6 immediately reveal several important features. Firstly, the [N II] 6584 Å emission is characteristic of an expanding, hollow shell of gas whereas the Hα emission appears to come from a large fraction of the nebular volume which also encloses an inner He II 6560 Å emitting volume. This is consistent with previous [O III] 5007 Å observations of a double shell structure. This is not unexpected in terms of ionisation stratification, but does pose serious problems if the PN evolution is interpreted solely in terms of the interacting stellar winds models, where the very hot and tenuous wind from the central star is predicted to evacuate a hot bubble whose gas pressure drives and supports the much more dense but relatively slowly expanding visible PN shell.

Incidentally, with an [N II] 6584 Å expansion velocity of 35 km s^{-1} and by adopting the Benedict et al.(2003) parallax distance of 420±60 pc and an angular radius along the minor axis of 3′ we get a true radius of 0.36 pc and a dynamical age for this

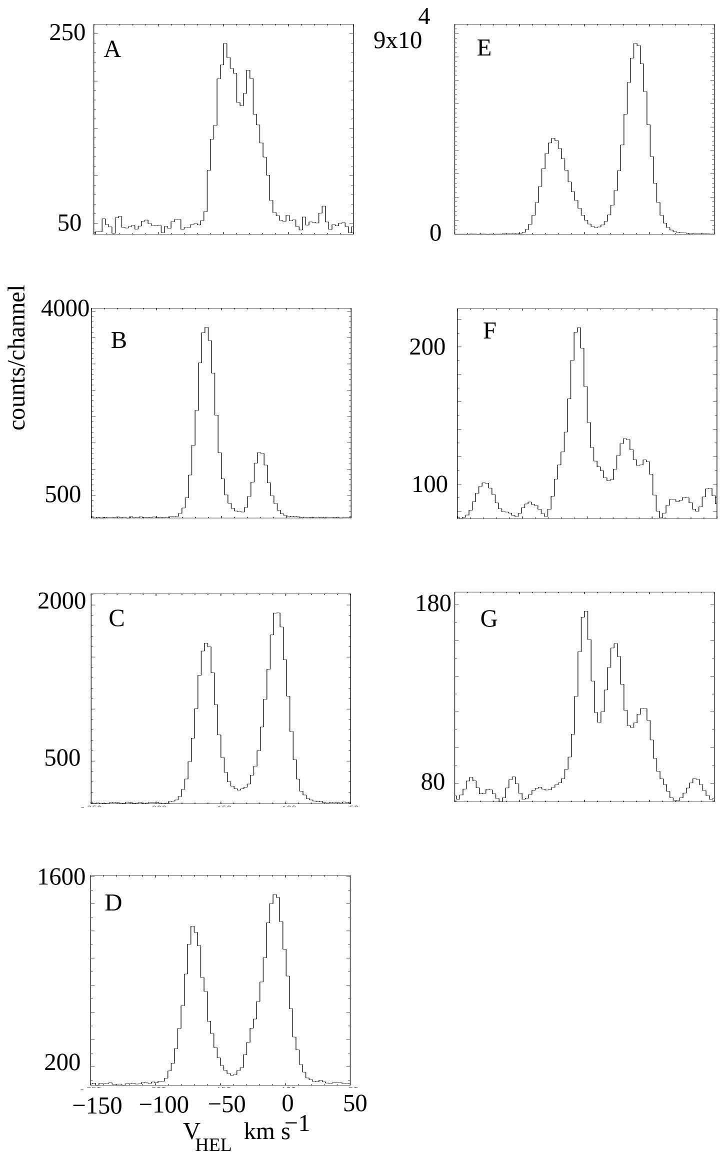

Fig. 5. Sample [N II] 6584 Å line profiles from 3 arcsec long increments along the NW-SE slit from the position marked A-G in Fig. 3.

inner bright structure of about 9000 years which must then be a lower limit for the true age of the [N II] 6584 Å shell.

The Dumbbell could though, as a well-evolved PN, have a star no longer producing the fast wind when in the white dwarf cooling region. In fact, Cerruti-Sola & Perinotto (1985) and Patriarchi & Perinotto (1991) fail to detect any fast wind from the central star in the IUE observations. In this case the two-winds model may have been valid in the early stages of the Dumbbell's evolution as the star crossed the HR diagram horizontally. With the later decline of the wind the bubble pressure would decrease and no longer balance the pressure of the expanding shell of ionized gas with a consequent acceleration of its inner layers towards the nebular centre. The increase in expansion velocities from the core to the [N II] 6584 Å emitting shell reported here are consistent with this viewpoint.

It is also desirable to consider the alternative possibility which involves 'mass-loading' of the fast wind as it percolates through the interior clumpy medium (Hartquist et al. 1986). Evidence for the presence of neutral globules (as also seen in the Helix PN, Meaburn et al. 1998) is shown in Meaburn & López (1993) and in the expanding CO emitting

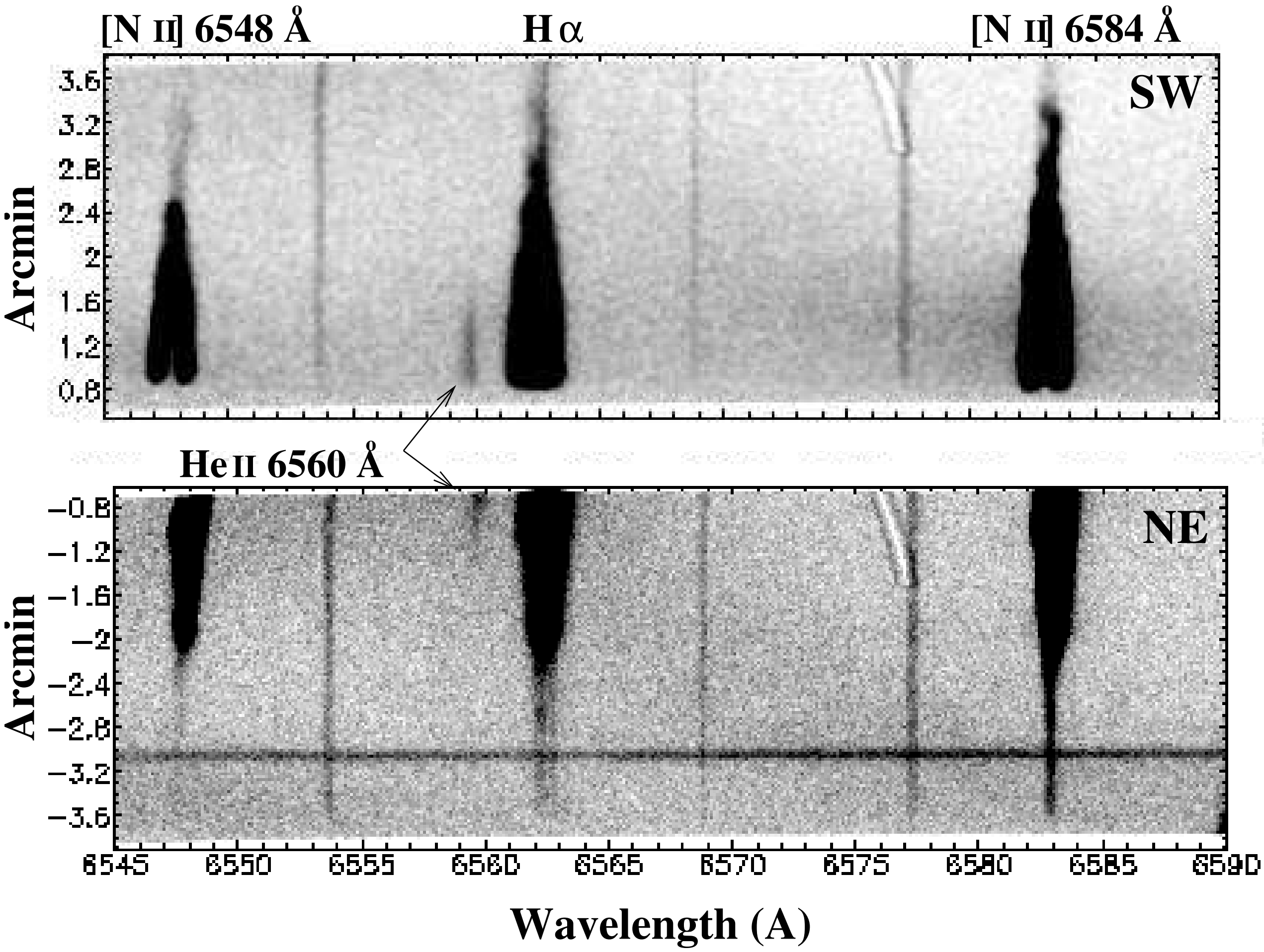

Fig. 6. Negative grey-scale representations of the pv arrays of He II 6560 Å, Hα and [N II] 6548 and 6584 Å profiles are shown for only the end slit lengths of the SW-NE line of measurments in Fig.2. The Hα and [N II] 6584 Å line profiles from the faint PN halo can be seen at the top end of the SW slit and the bottom end of the NE one. The dark horizontal band in the second panel is the continuous spectrum of a star image which has also fallen on the slit. An instrumental artifact and airglow spectra are also present.

shell observed by Huggins et al. (1996). It could be this slower mass-loaded momentum-conserving outflow that is seen as the [N II] 6584 Å emitting outer shell, itself clumpy. The 'V-shaped' flows arrowed in Fig. 3 could themselves be generated as this wind encounters further neutral globules (see Steffen & López 2004 for numerical simulations of this process).

The possibility that the shape of the halo (see Fig. 1) has been modified by the passage of the nebula through the ambient interstellar medium (as suggested by Papamastorakis et al. 1993) has been reinforced by the recent proper motion measurements of Benedict et al. (2003).These predict a tangential velocity of 37 km s^{-1} along PA 21±1° (Fig. 1a) of the central star which is in exactly the direction expected if this motion has influenced the shaping of the halo (see Fig. 1a). As differential galactic rotation only gives a tangential velocity component of −8 km s^{-1} and a radial velocity component of 5 km s^{-1}(to be compared with $V_{\rm SYS} = -41$ km s^{-1}—see Fig. 4) at this galactic longitude (l = 60.8°) the nebula must then have a substantial velocity with respect to its ambient medium. The low turbulent velocities (≤ 20 km s^{-1}) reported here on the inner edge of the NE part of the clumpy halo are consistent with its origin in the AGB superwind.

4. CONCLUSIONS

The bright [N II] 6584 Å emitting shell of the Dumbbell nebula is shown to be expanding radially at 35 km s^{-1} along its minor axis but to be 'quasi-ellipsoidal' or 'barrel-shaped' along its major axis.

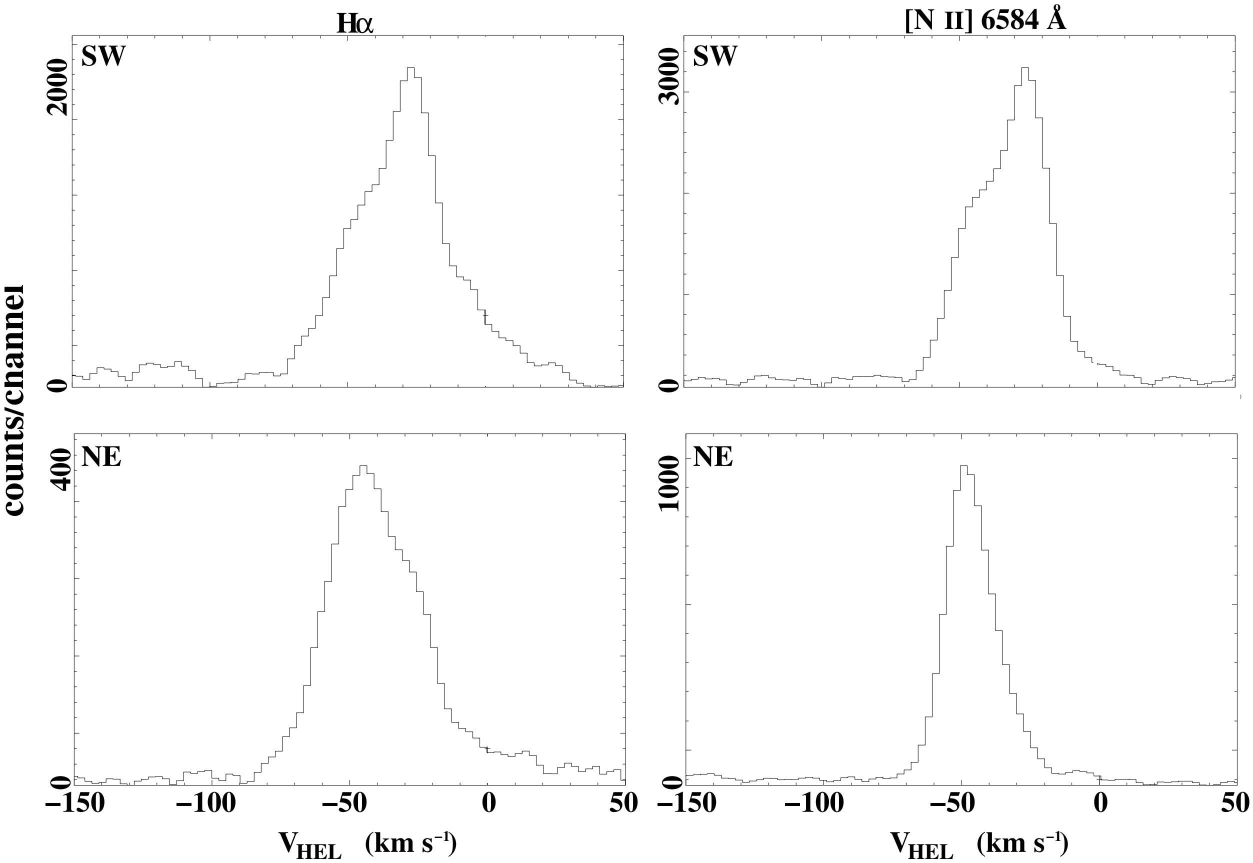

Fig. 7. Hα and [N II] 6584 Å line profiles of the halo from the pv arrays in Figs. 3 and 6, are presented. The halo profiles have been obtained for two lengths of the slit. Those designated SW are for the top 36″ length of the slit and those designated NE are for the bottom 48″length.

The Hα emission from this bright region is more diffuse and seems to fill much of the volume inside, and including, the outer [N II] 6584 Å shell. This is confirmed by the presence of an inner [O III] 5007 Å shell (expanding at 12 km s^{-1}) surrounding an He II 6560 Å emitting volume expanding at ≤ 7 km s^{-1}.

The detailed kinematics of the [N II] 6584 Å shell are characterised by 'V-shaped' outflows in the pv arrays which are around 10″ across. It proposed that these could be formed as the expanding [N II] 6584 Å emitting shell (possibily composed of a mass-loaded wind) encounters slow moving dense globules.

Line widths of ≈ 20 km s^{-1} from the knotty, faint outer halo are observed just outside the bright nebulosity. An expansion velocity for this outer halo of ≤ 10 km s^{-1} is indicated in which case the bright [N II] 6584 Å emitting shell is colliding with a differential velocity of ≥ 25 km s^{-1}.

The shape of the halo appears to have been affected by the passage of the nebula through the ambient interstellar medium.

The present data indicate that the global kinematic pattern of the Dumbbell nebula cannot be understood in simple terms from the expected behaviour predicted by the interacting winds model. Since the stellar wind from the central star seems to have ceased or declined substantially, lack of inner support for bubble pressure could have modified the shell expansion pattern, producing fall back acceleration, in agreement with the observations.

JM wishes to thank the staff of the WHT (La Palma) for their help during these observations. This research has made use of data (POSS-II) obtained through the STScI Center Online Service (CASB), provided by the California Institute of Technology. Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology-Hellas and the Max-Planck-Institut für Extraterrestrische Physik. JAL is grateful to the Royal Society and Academia Mexicana de Ciencias for financing his July 2004 stay in Manchester.

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