The creation of the Helix planetary nebula (NGC 7293) by multiple events

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ABSTRACT

A deep, continuum–subtracted, image of NGC 7293 has been obtained in the light of the Hα+[N II] emission lines. New images of two filamentary halo structures have been obtained and the possible detection of a collimated outflow made.

Spatially resolved, longslit profiles of the Hα+[N II] lines have been observed across several of these features with the Manchester echelle spectrometer combined with the San Pedro Martir 2.1–m telescope; these are compared with the [N II] 6584 Å, [O III] 5007 Å, He II 6560 Å and Hα profiles obtained over the nebular core.

The central He II emission is originating in a ≈0.34 pc diameter spherical volume expanding at ≤12 km s⁻¹ which is surrounded, and partially coincident with an [O III] 5007 Å emitting inner shell expanding at 12 km s⁻¹. The bright helical structure surrounding this inner region is modelled as a bi–polar nebula with lobe expansions of 25 km s⁻¹ whose axis is tilted at 37° to the sight line but with a toroidal waist itself expanding at 14 km s⁻¹.

These observations are compared with the expectations of the interacting two winds model for the formation of PNe. Only after the fast wind has switched off could this global velocity structure be generated. Ablated flows must complicate any interpretation.

It is suggested that the clumpy nature of much of the material could play a part in creating the radial ‘spokes’ shown here to be apparently present close to the central star. These ‘spokes’ could in fact be the persistant tails of cometary globules whose heads have now photo–evaporated completely.

A halo arc projecting from the north–east of the bright core has a counterpart to the south–east. Anomolies in the position–velocity arrays of line profiles could suggest that these are part of an expanding disc not aligned with the central helical structure though expanding bi–polar lobes along a tilted axis are not ruled out.

Key words: circumstellar matter; Helix Nebula; NGC 7293

1 INTRODUCTION

The multitude of phenomena in the Helix planetary nebula (NGC 7293, PK 36–57°1) at a distance of only 213 pc (Harris et al 1997) can be investigated over a uniquely wide range of spatial scales for at that distance 1″ ≡ 3.19 × 10¹⁵ cm. It is therefore proving to be one of the most important laboratories for the investigation of all aspects of evolved planetary nebulae (PNe).

The progenitor star is a low luminosity (L/L⊙ ≈ 100 Henry, Kwitter & Dufour 1999) white dwarf (WD 2226–210, Mendez et al 1988) with an effective temperature of 117,000 K and mass 0.93 M⊙ (Górny, Stasinska & Tylenda 1997) as well as a late–type dMe companion whose halo is responsible for hard X–ray emission (Chu et al 2004; Gruendl et al 2001). Patriarchi & Perinotto (1991) discovered that 60 percent of central stars of PNe emit particle winds from 600 – 3500 km s⁻¹ but failed to detect one from WD 2226–210. In fact, Cerruti–Sola & Perinotto (1985) had given an upper limit to such a wind as ≤ 10⁻¹⁰ M⊙ yr⁻¹ which has implications for the dynamics of NGC 7293 (see Sect. 4.1). The lowly ionised, apparently helical, structure that gives the nebula its name could be a toroid with bi–polar lobes viewed at ≈ 37° with respect to the bi–polar axis (Meaburn et al 1998; Henry, Kwitter & Du–
four 1999) though O’Dell, McCullough & Meixner (2004) present an alternative view (Sect. 3.2). Whatever form this helical structure takes it contains an [O III] emitting shell on the inside surface of the toroid with an inner [O III] emitting shell (Meaburn & White 1982; O’Dell et al 2004) surrounding a highly ionised He II emitting central spherical volume shown particularly well by O’Dell et al (2004) and considered by Henry et al (1999). This bright central nebula is surrounded by faint filamentary structure as shown in different ways by Malin (1982), Walsh & Meaburn (1987), Speck et al (2002) and O’Dell et al (2004).

The whole ionized nebula is enveloped within a massive envelope of molecular gas (Storey 1984; Huggins & Healey 1989; Healey & Huggins 1990; Forveille & Huggins 1991; Young et al 1999).

Arguably the most interesting feature of the ionised helical structure are the multitude of ‘cometary’ knots inhabiting its inside surface. These have dense neutral cores (Meaburn et al 1992, 1998; Huggins et al 1992) with long ionised tails pointing radially away from the central star seen in superb detail in the HST images of O’Dell & Handron (1996).

In the present paper, spatially resolved profiles of the Hα and [N II] 6584 Å emission lines are compared with new continuum-subtracted emission line images of the most prominent halo feature. Furthermore, the kinematics of the nebular core are explored with longslit profiles of the [O III] 5007 Å and He II 6560 Å emission lines. The central motions are then compared with previously published data and the implications for current dynamical models for the creation of PNe are considered. Furthermore, the bipolar/toroidal model of the bright helical structure is tested by numerical simulations compared in detail with observations. The origin of strange radial ‘spokes’ of enhanced [N II] emission is also explored.

2 OBSERVATIONS AND RESULTS

2.1 Wide-field imagery

The image of NGC 7293 shown in Figs. 1a–c was obtained with the 0.3–m (f/3.2) Schmidt-Cassegrain telescope at Skinakas Observatory, Crete, Greece in 2003 July 30. The 1024×1024 (19×19 µm²) pixels Thomson CCD camera was used resulting in a scale of 4′.1 pix⁻¹ and a field of view of 70′×70′. Five exposures in Hα+[N II] of 2400 s each were taken during the observations (resulting in a total integration time of 12000 s), while three exposures of 240 s were obtained with the continuum filter. The latter were subtracted from the former to eliminate the confusing star field (more details of this technique can be found in Bounis et al 2002). The image reduction (bias subtraction, flat-field correction) was carried out using the standard IRAF and MIDAS packages. The astrometry information was calculated using stars from the Hubble Space Telescope (HST) Guide Star Catalogue (Lasker et al. 1999). Although many of the features shown in Fig. 1a & b are previously known (see refs. in Sect. 1 and particularity O’Dell et al 2004) this unique wide-field continuum-subtracted image relates them to each other clearly. The very deep presentation in Fig. 1c) reveals a bow-shaped feature and possible, but tenuous, counter–jet both of which are arrowed.

2.2 Longslit spectroscopy

2.2.1 Hα & [N II] 6584 Å profiles from the halo

The longslit observations were obtained with the Manchester Echelle Spectrometer (MES - Meaburn et al, 1984 & 2003) combined with the I7.9 focus of the 2.1–m San Pedro Mártir UNAM telescope on 28 June 1998. This echelle spectrometer has no cross-dispersion. For the present observations, a filter of 90 Å bandwidth was used to isolate the 87th order containing the Hα and [N II] nebular emission lines.

A Tektronix CCD with 1024×1024 square pixels, each with 24 µm sides, was the detector. Two times binning was employed in both the spatial and spectral dimensions. Consequently 512 increments, each 0.60′ long, gave a total projected slit length of 5.12′ on the sky. ‘Seeing’ varied between 1–2′ during these observations. The slit was 150 µm wide (≃11 km s⁻¹ and 1.9′) and the integration times were 1800 s. The spectra were calibrated in wavelength to ±1 km s⁻¹ accuracy against that of a Th/Ar arc lamp and in absolute surface brightness (of the Hα line) to an accuracy of ±20 percent against a slitless spectrum of the ‘standard’ star Feige 56.

The three slit positions (1–3) over the halo feature of NGC 7293 are shown in Fig. 2 against part of the image in Fig. 1. Greyscale representations of the resultant position–velocity (pv) arrays of Hα and [N II] profiles are shown in Figs. 3–5 respectively.

2.2.2 He II 6560 Å and [O III] 5007 Å profiles from the core

Previously (Meaburn et al 1996, 1998) Hα and [N II] profiles were obtained with MES on the Anglo–Australian (3.9–m) telescope (AAT), from NS and EW lines of measurements, each 1000 arcsec long, through the central star of NGC 7293. Spectra from many slit lengths were combined to cover such large regions (see the above papers for all technical details). For comparison with the present spectral observations the pv array of the individual velocity components in the [N II] 6584 Å profiles along the EW line of measurements is shown in Fig. 6 (from Meaburn et al 1996).

A re-examination of these previous pv arrays revealed that the high excitation He II 6560 Å emission line, from an area of ≈200′′ radius around the nebular core, was detected in this previous data. This detection is illustrated in the greyscale representation of the whole EW longslit spectrum shown in Fig. 7. and the relative surface brightness profile of this He II 6560 Å emission (see Table 1) compared with that of the [N II] 6584 Å emission along the same EW slit lengths is shown in Fig. 6. The He II brightness profile from O’Dell et al (2004) and that shown here for He II 6560 Å in Fig. 6 suggests that the HeII emitting region is a roughly spherical volume.

Each He II 6560 Å profile was extracted for the incremental lengths along the EW slit lengths listed in column 1 of Table 1. Each profile was simulated by a least squares best fit single Gaussian profile whose observed centroid, corrected for heliocentric motion (1994 20 Sept.) is given in column 2 and observed halfwidth in column 3 of Table 1. These observed profiles are intrinsically broadened by the 19 fine structural components spread between 6559.769–6560.209 Å which is ⅒ km s⁻¹ range (see the ‘Atomic Line List’ in http://www.pa.uky.edu/~peter/atomic/).

Following Clegg et al (1999), who calculated the relative brightnesses for the fine structural components of other He II lines, the relative brightnesses of the 19 components for He II 6560 Å, within Menzel’s Case B, for electron densities of n_e = 100 and 1000
assuming that all broadening functions are Gaussian. Finally the thermal and instrumental broadenings, for these are well known, Table 1 are the observed halfwidths in column 3 corrected for both and d) radial expansion of the same volume which is the parameter of particular interest. The corrected halfwidths in column 4 of Table 1 are the observed halfwidths in column 3 corrected for both thermal and instrumental broadenings, for these are well-known, assuming that all broadening functions are Gaussian. Finally the relative He II 6560 Å profile brightnesses in column 5 are the mean values per increment for the whole of the line profiles along the incremental lengths in column 1. The continuum emission adjacent to the He II 6560 Å line (see Fig. 7) was subtracted in this process. The profiles from the last two incremental lengths listed in Table 1 were so faint that only their relative surface brightnesses could be measured with significant accuracy.

\[ \text{He II} \] and \[ \text{He II} \] 6560 Å profiles extracted from a sample length of 60 arcsec centred to the east of the central star (see Fig. 7) are shown in Fig. 8. This range just excluded contamination by the stellar spectrum and gave the highest signal to noise ratio for the critical but faint \text{He II} 6560 Å line. A similar detection of \text{He II} 6560 Å emission was made in the NS spectrum (not shown).

The core of the central spherical volume of \text{He II} 6560 Å emission is surrounded, and partially coincident with, an inner shell of \[ \text{O III} \] 5007 Å emission whose emission peaks are separated by \( \approx 240 \) arcsec (Meaburn & White 1982 and see Fig. 4 in O’Dell et al 2004). This shell can be seen clearly in the deep negative representation of the \[ \text{O III} \] 5007 Å image taken with the New Technology Telescope (La Silla) in Fig. 9 (see Meaburn et al 1998 for the technical details). Spatially resolved \[ \text{O III} \] 5007 Å line profiles were obtained with MES combined with the AAT along the 163 arcsec long E-W slit marked in Fig. 9. The integration time was 1800 s and slit width 70 µm (\( \approx 6 \) km s\(^{-1}\) and 0.5 arcsec on the sky). Again the technical details of this as yet unpublished observation are given in Meaburn et al (1998). Co-added profiles were obtained for all blocks, 5 increments long, along the 512 CCD increments that covered the slit length. The separate velocity components in each of these profiles were simulated by Gaussians whose centroids are shown in Fig. 9. Over the central star (at 0 arcsec offset in Fig. 9) it can be seen that four velocity components in the \[ \text{O III} \] 5007 Å profiles are present (i.e. at \( v_{hel} = -60, -42, -17 \) and \(-4\) km s\(^{-1}\)). The \[ \text{O III} \] 5007 Å line profile for an incremental length comparable to that used for the \( \text{H}_\alpha, \text{N I} \) 6584 Å and \text{He II} 6560 Å profiles is also shown in Fig. 8.

### 2.3 Imagery of radial ‘spokes’

The cometary knots have dense, molecular heads (Meaburn et al 1992 and Huggins et al 1992) with tails extending away from the central stars. O’Dell et al (fig. 16 – 2004) and Henry et al (fig. 5 – 1999) have revealed even more widespread system of headless ‘spokes’ in the \[ \text{N I} \] emitting gas extending from the inner torus outwards in the bright nebulosity. Henry et al (1999) showed them as parallel ridges of enhanced \[ \text{N I} \] emission by dividing their \[ \text{N I} \] image with their \( \text{H}_\alpha \) one.

### Table 1. Measured parameters of the He II 6560 Å profiles along the EW slit lengths.

| Extracted length | Observed central wavelength (Å) | Observed halfwidth (Å) | Corrected halfwidth (km s\(^{-1}\)) | Profile brightness (relative units per increment) |
|------------------|---------------------------------|-----------------------|-----------------------------------|-----------------------------------------------|
| -64 to -27       | 6559.49 ± 0.06                  | 0.61 ± 0.10           | 23 ± 4                            | 0.90                                          |
| -25 to -5        | 6559.50 ± 0.06                  | 0.68 ± 0.05           | 27 ± 2                            | 0.94                                          |
| 10 to 35         | 6559.54 ± 0.04                  | 0.68 ± 0.05           | 24 ± 2                            | 1.00                                          |
| 35 to 60         | 6559.53 ± 0.05                  | 0.61 ± 0.15           | 23 ± 5                            | 0.96                                          |
| 60 to 85         | 6559.53 ± 0.03                  | 0.62 ± 0.08           | 24 ± 3                            | 0.84                                          |
| 85 to 110        | 6559.53 ± 0.03                  | 0.62 ± 0.04           | 24 ± 1                            | 0.64                                          |
| 110 to 160       | 6559.54 ± 0.05                  | 0.55 ± 0.04           | 20 ± 1                            | 0.38                                          |
| 160 to 180       | -                               | -                     | -                                 | 0.19                                          |
| 180 to 200       | -                               | -                     | -                                 | 0.11                                          |

### Table 2. Relative strengths of the He II 6560 Å line fine–structure components normalized to the brightest component (6560.1848 Å).

| Fine structure components of He II 6560 Å (6 → 4) | Relative Strengths (CASE B, T = 10⁴ K) |
|--------------------------------------------------|---------------------------------------|
| 6559.7687                                        | 0.0535                                |
| 6559.7940                                        | 0.0532                                |
| 6559.8544                                        | 0.0184                                |
| 6560.0523                                        | 0.2983                                |
| 6560.0528                                        | 0.0963                                |
| 6560.0832                                        | 0.0011                                |
| 6560.0839                                        | 0.0107                                |
| 6560.1416                                        | 0.7709                                |
| 6560.1418                                        | 0.4268                                |
| 6560.1571                                        | 0.0001                                |
| 6560.1573                                        | 0.0213                                |
| 6560.1696                                        | 0.0368                                |
| 6560.1766                                        | 0.0056                                |
| 6560.1848                                        | 1.0000                                |
| 6560.1882                                        | 0.0016                                |
| 6560.1883                                        | 0.0101                                |
| 6560.1941                                        | 0.0285                                |
| 6560.2096                                        | 0.0023                                |
An image of 1800 s duration through a 72 Å bandwidth filter centred on Hα + [NII] was obtained with the NTT (see Walsh & Meaburn 1993; Meaburn et al 1998 for the technical details) and is shown at high contrast in Fig. 10. The outer radial ‘spokes’ can be seen to continue faintly inside the disk containing the cometary globules to within ≈ 30′′ from the central star. They are seen to be radially distributed with respect to the central star and continuous in some cases with the more recently discovered, but similar features in the adjacent bright helical structure (O’Dell et al 2004; Henry et al 1999). For these reasons they are considered to be real and shown here at high contrast. Obviously a deep, reasonably high resolution, image in the same emission lines is needed to confirm their presence for the image in Fig. 10 is not flat-fielded. However, these spokes are relevant to the understanding of cometary globule formation and knot evaporation.

3 KINEMATICS AND MORPHOLOGIES

3.1 HeII 6560 Å volume and [OIII] 5007 Å inner shell

The presence of the HeII 6560 Å volume close to the central star affects many of the theoretical ideas for the creation of planetary nebulae consequently its structure and motions should be quantified. The HeII 4686 Å image of O’Dell et al (2004) suggest that it is a spherical volume of ≈ 180′′ radius. This morphology is confirmed by the relative brightness distribution here in Fig.6. The widths of the HeII 6560 Å line profiles when corrected for thermal and instrumental broadenings (column 4 of Table 1) have a maximum width of 26 ± 2 km s⁻¹ near the central star with only a minor (and uncertain) decline in width up to 160 arcsec from this star. As this width will also contain the consequences of fine structural width and turbulent motions then the 13 ± 2 km s⁻¹ is very much an upper limit to the radial expansion of the HeII 6560 Å emitting volume. If turbulent motions of ≥ 10 km s⁻¹ (flows at the sound speed off globule surfaces for instance) contribute to the line width in addition to a fine structural broadening component of ≈ 6 km s⁻¹ then a global expansion of the HeII 6560 Å emitting region would be ≤ 12 km s⁻¹. The non-Gaussian shape of the HeII 6560 Å profile in Fig. 8 could suggest that an expansion velocity near this upper limit is in fact present.

The inner [OIII] 5007 Å emitting shell in Fig. 9 is co-existent with the outer, and faint, parts of the HeII 6560 Å emitting volume. The splitting of 25 km s⁻¹ of the [OIII] 5007 Å profile over the central star, which is symmetrical around Vsys, undoubtably is caused by radial expansion of 12.5 ± 1.0 km s⁻¹ of the inner [OIII] 5007 Å emitting shell. This value is now considered to be more realistic than the ≈ 20 km s⁻¹ given in Meaburn et al (1998) derived from Fabry–Perot observations in Meaburn & White (1982 - one velocity component was misinterpreted).

Incidentally, because this HeII 6560 Å emitting region is relatively inert and so close to the central star, and because it is a single recombination line with a well known wavelength though complicated by fine structural components, a bi-product of the present HeII 6560 Å profile measurements is a reliable value of the systemic heliocentric radial velocity (Vsys) for NGC 7293. As the mean observed central wavelength is 6560.053 ± 0.015 Å (mean of values in column 2 of Table 1) and with the mean rest wavelength, with each fine structural component weighted by its relative brightness in Table 2, is 6560.128 Å and as Vhel = Vobs −24.3 km s⁻¹ on the date of observations then Vsys = −27.1 ± 2.0 km s⁻¹ when systematic calibration uncertainties are included. This is consistent with a previous, though less certain, value of Vsys derived from the centroids of the split [NII] 6584 Å profiles over the central star (Meaburn et al 1998); the [NII] 6584 Å components are not necessarily symmetric around Vsys.

3.2 The bright helical structure

The bright helical structure emitting [NII] 6584 Å can be seen in Meaburn & White (1982) and O’Dell et al (2004) to be enclosing an ‘outer’ [OIII] 5007 Å emitting shell, the ‘inner’ [OIII] 5007 Å shell shown in Fig. 9 as well as the central HeII 6560 Å emitting volume (see Fig. 6). It was proposed in Meaburn et al (1998) that this helical structure could be a consequence of bi-polar lobes expanding from a toroidal ring, itself expanding radially. As O’Dell et al (2004) challenged this assertion the kinematics and morphology of the [NII] 6584 Å helical structure has been further explored using the XSHAPE code developed by Steffen, Holloway & Pedlar (1996) and Harman (2001). This numerical technique does not give a unique answer but does predict accurately the observed surface brightnesses and spatially resolved radial velocity shifts of emission lines for any predetermined structure.

In the present case a starting point for this modelling is to identify as B and C the manifestation of the central toroid in the E–W pv array in Fig. 6. These positions coincide with major brightness maxima and have radial velocities nearly symmetrically displaced from Vsys = −27 km s⁻¹. Undoubtedly the ionised inside surface of a larger, radically expanding, molecular toroid (Healey & Huggins 1990) is being observed at an angle in agreement with O’Dell et al (2004). In the very simplest of bi-polar models the positions A and D in Fig. 6 are where these sight lines intersect the edges of the lobes. As the observed radial velocities at both of these positions are close to Vsys this supposition is reasonable if it is assumed that lobe expansion is always proportional to the distance from the central star and along a vector pointing away from this centre.

The model shown in Fig. 11 is based on these assumptions and using the XSHAPE code the predicted morphology is compared to the observed image from Fig. 1 and the negative greyscale representations of both the observed N–S and E–W pv arrays of [NII] 6584 Å profiles from Meaburn et al (1998). The positions A – D marked in Fig. 6 are also shown.

In this model the tilt of the sightline to the nebular axis is 37°, the radial expansion of the toroid (B & C) is 14.25 km s⁻¹ and the expansion of the two lobes 24.5 km s⁻¹ along the bipolar axis. Each lobe has the shape of an inverse ellipsoid (sphered by an ellipse) with semi–major axis of 490” and semi-minor 285”. To give the appearance of reality, clumps are distributed randomly within the 3D grid with 0.0001 clumps per cubic arcsec. Each clump has the form of a 3D Gaussian with FWHM of 20”. The simulated image has been smoothed with a 10’’ wide Gaussian to match the resolution in Fig. 1. The simulated pv arrays have been convolved with the 11 km s⁻¹ wide instrumental profile. A convincing, though obviously not perfect, fit of the model predictions to the salient features of the observed image and the two orthogonal pv arrays is demonstrated in Fig. 11. These observations and model cannot accommodate the presence of two tilted rings as suggested by O’Dell et al (2004).

The model in Fig. 11 is only for the bright [NII] 6548, 6584 Å emitting helical structure which has its CO emitting inner counterpart (Young et al 1999). O’Dell et al (2004) suggest that the inner ring (whose edges are marked as B and C in Fig. 11) is an expanding disk as modelled here. However, they go on to suggest that the two adjacent bright arcs (whose edges are at A and D respectively
in Fig. 11) are the manifestation of a single expanding disk expanding orthogonally to the central disk. They base this assertion solely on fig. 5 of Young et al. (1999) where an orthogonal range of velocities for a CO ‘outer arc’ is partially detected. The excellent morphological and kinematical fit of the model in Fig. 11 (and see fig. 9 of Young et al 1999) suggests that this interpretation is incorrect. An outer partial CO ring, expanding orthogonally but faint in [N II] 6548, 6584 Å (Young et al 1999) must exist but is not part of the bright [N II] 6548, 6584 Å emitting helical structure modelled here.

3.3 The halo

The nebulous N–E halo arc imaged by Malin (1982) and see also Speck et al (2002) and shown in Fig. 1b and Fig. 2 has a S–W counterpart which could suggest some form of bi–polar structure which is both larger and along a different axis to that proposed for the bright helical nebulosity. However, the pv arrays of [N II] 6584 Å profiles in Figs. 3–5 along slits 1–3 in Fig. 2, and those of Walsh & Meaburn (1987) reveal behaviour not easily explained in a model involving classical three dimensional bi–polar lobes. For instance, although there is a systematic trend in radial velocity from the north of slit 2 ($V_{\text{hel}} = 0\ \text{km s}^{-1}$) to the southern end where $V_{\text{hel}} = -60\ \text{km s}^{-1}$, which suggests some form of expansion, the bright northern edge would be expected at $V_{\text{sys}} = -26\ \text{km s}^{-1}$ in a simple bi–polar model. The eastern edge itself was shown to have complex velocity structure with an extreme velocity component at $V_{\text{hel}} = -80\ \text{km s}^{-1}$ (slit 3 in Fig. 5 and also see Walsh & Meaburn 1987). Nevertheless, line splitting observed in slit positions 2 & 3 (Figs. 4 & 5) suggests the interpretation of these features as expanding lobes though not orthogonal to the central torus which is modelled in Fig. 11. A similar case is observed in NGC 2440 (López et al. 1998).

An alternative possibility is that both this eastern and western halo structure could rather be both parts of a single expanding ring of ionised material. If so it must be oriented at a completely different angle to the central torus (BC) shown in Fig. 11 for the eastern edge has predominantly approaching radial velocities with respect to $V_{\text{sys}}$. If these reflect the radial expansion of the ring then its expansion could be as high as $\approx 70\ \text{km s}^{-1}$ for an arbitrary tilt of 45° to the sight line although the observed radial velocities do not unambiguously favour this ring model.

More observations at similar spectral resolution, particularly of the south–western halo lobe, are required to investigate these propositions more fully.

Other features of the general halo of NGC 7293 have been seen previously (e.g. O’Dell et al. 2004) but of potential interest is the faint jet–like feature in the SW, along PA 255°, but projecting back to the nebular core in the deep image in Fig. 1c. A bow–shaped possible counter feature on the opposite side of the nebula is aligned with it.

4 DISCUSSION

4.1 The interacting winds model

PNe are a consequence of the sequence of events as a star of $\lesssim 8\ \text{M}_\odot$ evolves through its Red Giant (RG) and Asymptotic Giant Branch (AGB) phases to finally become a White Dwarf (WD). In this sequence it is generally accepted that an initial RG wind, is followed by the more volatile and many times denser AGB ‘superwind’ (with sporadic outbursts at 20 of $\text{km s}^{-1}$) which is then subjected to interaction with a high–speed wind (several 1000 $\text{km s}^{-1}$) and becomes photo–ionised as the central star becomes a WD with a high surface temperature. At this point the circumstellar envelope becomes the embryo PN. The fast wind could then decline as the star becomes an older WD and the photoionised circumstellar envelope would then be described as an evolved PN.

The standard interacting winds (IW) model (Kwok, Purton & Fitzgerald 1978; Khan and West 1985; Chu, Kwitter & Kaler 1993; Balick & Frank 2002) makes a theoretical attempt to explain the formation of the observed nebular structure and kinematics in PNe during the transition of the stellar core from the post–AGB to the WD stages. Here, with smooth, isotropic, density distributions the fast wind forms an expanding pressure driven (energy conserving) bubble in the pre–cursor AGB wind. A central volume of unshocked fast wind is surrounded by a shell of superheated ($10^9\ \text{K}$) shocked wind which provides the gas pressure to form and accelerate a shell of shocked AGB wind. Within this model and with photo–ionisation dominant the latter expanding, low–ionisation, shell is characteristic of young PNe. Balick & Frank (2002) emphasise that from observations of a large number of PNe this model, although an excellent theoretical starting point, is very idealistic; there are a multitude of phenomena within PNe when the stars are in their post–AGB phases that require more complex explanations; lobes and disks expanding along separate axes being only two of many such complexities.

The present kinematical observations of the undoubtedly evolved PN, NGC 7293, reported here could be consistent with the final stages of the IW model if it is assumed that the fast wind has now switched off. This possibility is made plausible by the absence of a direct observation of the fast wind in the stellar spectrum (see Sect. 1) and the very presence of an inner He II 6560 Å volume and [O III] 5007 Å shell would prevent the direct interaction of such a wind with the outer helical structure. The progression outwards of the expansion velocities i.e. $\leq 12\ \text{km s}^{-1}$ for the He II 6560 Å emitting centre, 13 km s$^{-1}$ for the surrounding inner [O III] 5007 Å shell and 25 km s$^{-1}$ for the [N II] 6584 Å emitting outer envelope albeit inside an outer bi–polar configuration (Fig. 11), could be a consequence of the sudden pressure decline that would occur as the fast wind switched off leading to acceleration inwards of the now unsupported inner regions of the previous pressure driven shell (private comms. by Steffen and Dyson). Incidentally, Wilson (1950) had noticed this increasing velocity from the high–ionisation centres to low–ionisation envelopes of many similarly evolved PNe.

However, the clumpy nature of most of the circumstellar material also poses a direct problem for the IW model (see Sect. 4.2).

4.2 Cometary knots and [N II] 6584 Å ‘spokes’

The radial ‘spokes’ that are prominent in the bright helical nebulosity and shown here to extend, faintly, to within 30° of the central star are most likely a consequence of the clumpy nature of the nebula.

Such a clumpy structure is to be expected when the whole of NGC 7293 is considered for it is famous for its cometary globules beyond a radius of 90° from the central star. These were first shown to have dense molecular cores directly by Huggins et al. (1992) and by Meaburn et al (1992) when silhouetted against the central [O III] 5007 Å emission. Dyson et al. (1989) had suggested that the cometary globules were a consequence of the ejection of the RG maser spots as dense globules later overrun by the faster AGB wind. If this clumpiness extends to the nebular core it would suggest that clump ejection had occurred with a wide spread of ejection veloc-
ities. The system of well-known cometary globules is expanding radially within the central torus at 14 km s$^{-1}$ consistent with their RG origin (Meaburn et al 1998).

The headend radial 'spokes' could then all be relics of cometary tails from globules that have nearly photoevaporated. The inner 'spokes' in Fig. 10 could be elongated enhancements of [N II] 6584Å emission either in the torus containing the cometary globules, extending inwards, or in the walls of the lobes in the model in Fig. 11 but pointing always towards the central star. In the latter case they are then seen in projection over the inner [O III] 5007 Å and He II 560 Å emitting core of the nebula.

The recombination time T of hydrogen is $\approx 10^5 n_e^{-1} \text{yr}$ then for a tail electron density $n_e = 50 \text{ cm}^{-3}$, $T \approx 5000 \text{yr}$. A longer recombination time in the lower density ionised material of a tail, after the dense head of a cometary globule has evaporated, could on its own then explain the tail's persistence. A more detailed explanation could be given by López-Martín et al (2001) who have discussed the evaporation of the cometary globules and their tails (see also Cantó et al 1998). The clump heads are exposed to the direct ionising radiation of the central star while the tails are only exposed to the diffuse radiation field. This is typically a few percent of the direct field at the location of the bright optical knots but is very much less closer to the star because of the $r^{-2}$ rise in the direct flux (López-Martín et al 2001). For clumps that are close to the central star, recombinations in the evaporating head gas can not significantly absorb the stellar flux. In this case, the evaporation timescale is approximately (López-Martín et al 2001)

$$t_{\text{evap}} \approx \frac{R_c c_1}{c_0^2}$$  \hspace{1cm} (1)

where $c_1$ and $c_0$ are the sound speeds in the ionised and neutral gas respectively. Note especially the dependency in Eq. 1 on clump radius $R_c$: once a clump begins to shrink the evaporation timescale drops and the clump will then rapidly disappear. The tail will only begin to be exposed to the direct stellar radiation field when the clump shrinks appreciably. It is thus entirely plausible that the tail may survive the destruction of its parent clump. It will then be quickly ionised by the direct field and be very overpressured but as is clearly seen in Fig. 10 the clumpless tails have not yet had time to mix with the surrounding gas (for a tail of radius $10^{15}$ cm the dynamical timescale is a few thousand years in the ionized gas).

This predominance of clumps in the ionised envelope of NGC 7293 also makes it most likely that momentum–conserving, mass–loaded (ablated) flows (Dyson, Hartquist & Biro 1993) have played an important, even dominant, part in the evolution of this PN. A hybrid explanation, with the IW model applicable immediately after the onset of the fast wind followed by a domination of ablated flows up to the switch–off of the fast wind, may be a more appropriate way of considering the creation of NGC 7293. The velocity structure of the clumpy PNe such as NGC 7293 has been recently studied by Steffen & López (2004) where progressive expansion velocities with distance from the central star are obtained in the simulations.

4.3 The halo features

The extended ionised material beyond the bright inner regions (Fig. 1) was detected by Speck et al (2002) using Southern H–Alpha Sky Survey Atlas data (SHASSA–Gaustad et al 2001). Meanwhile, O’Dell et al (2002) carried out detailed photoionisation modelling of the bulk of the inner shell using CLOUDY. The modelling indicated that the nebula was ionisation bounded rather than density bounded yet the presence of the extended ionised gas is confirmed here and in O’Dell et al (2004). The apparent contradiction between the CLOUDY results of O’Dell et al (2002) may be explained in the following qualitative way. The very clumpy nature of the inner ring of NGC 7293 (the majority of the mass of the shell may even reside as molecules in the clumps– Speck et al 2002) means that it is possible, as long as the volume filling factor of the clumps is not too great, for the ionising radiation to escape the inner ring. The photoionisation modelling will yield results consistent with an ionisation bounded system simply because the bulk of the emission comes from the clump surfaces where the ionisation is locally bounded. Alternatively, O’Dell et al (2004) maintain that the central torus (BC in Fig. 11) is globally ionisation bounded and that the extended ionised gas lies above and below the plane of this torus. They also suggest that the extended ionised gas could have been ionised at an earlier epoch and owing to a low density has not yet recombeded.

The possibility that expanding lobes or even a disc of material (Sect. 3.3) exists in the halo of NGC 7293 is not unexpected when other PNe are considered. Multiple axes of ejection are observed in the PNe NGC 6302 (Meaburn & Walsh 1980), KIPn8 (López et al 2000), NGC 2440 (López & et al 1998) and J 320 (Harman et al 2004) for example. A similar high–speed disc is observed around the bi–polar lobes of Mz 3 by Santander–García et al (2004). These phenomena are most likely evidence of the volatility, and as yet not understood behaviour, of the AGB phase in the evolution of the central stars of PNe.

The possibility reported here of a jet and counter bow–shaped feature in the halo of NGC 7293 is again not unexpected when the whole range of observed phenomena are considered in PNe. Collimated outflows are seen in many PNe e.g. FG 1 (López, Roth and Tapia 1993, López, Meaburn & Palmer 1993) etc. There is at yet no consensus about their origin though they must be associated with the onset of the superwind as the stars enter their post–AGB phase with binarity of the central stellar systems playing some part in their generation.

5 CONCLUSIONS

Progressively increasing expansion velocities are observed from the highly ionised core of NGC 7293 to the lobes that constitute the lowly ionised helical structure.

Numerical simulations of the latter structure as bi–polar lobes, expanding perpendicularly to a central torus, give a reasonable match to the observed images and pv arrays of line profiles. The standard interacting winds model for the creation of PNe explains this kinematical and morphological structure only if the fast wind has switched off as the central star becomes a WD. Ablated flows must add a further complication to any dynamical considerations. Radial 'spokes' of [N II] emission which are now traced to near the central star could be the remnants of the cometary tails of dense globules that have now photo-evaporated. It is proposed that a prominent halo arc could be part of a single expanding disk along a different axis to that of the bright nebula although expanding bi–polar lobes along this same axis remain an interpretation. More extensive kinematical observations are needed to distinguish between these possibilities. A jet-like feature and its counter bow-shock are tentatively identified.
Figure 1. The same deep Hα+[N II] image is displayed at three contrast levels to show all of the features from the bright, inner helical structure out to the very faint halo regions (epoch 2000). The bow–shaped feature and jet–like feature are both arrowed in c).
Multiple events in the AGB phase, and shortly afterwards, of the central star must have created these phenomena.

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Figure 2. New slit positions (1–3) and the previous E–W continuous line of spectral measurements (Figs. 6 & 7) are shown against the Hα+[N II] image (Fig. 1).
Figure 3. Greyscale representations of the H$\alpha$ and [N II] 6584 Å profiles along slit position 1 in Fig. 2 are shown.
Figure 4. As for Fig. 3 but for slit 2
Figure 5. As for Fig. 3 but for slit 3.
Figure 6. In the top panel the centroids of individual velocity components in the [N II] 6584 Å profiles, from the long E–W length marked in Fig. 2, are compared to the halfwidths of the He II 6560 Å line profiles when corrected for both instrumental and thermal broadening (column 4 in Table 1. In the bottom panel the relative surface brightnesses (RSB) of the [N II] 6584 Å and He II 6560 Å profiles are compared. The dashed line is simply the western observed curve folded over to the eastern side (where it was below the detection limit). This is justified by the He II 6560 Å brightness variations observed along the NS slit (not shown). Key positions are marked A–D in both panels.
Figure 7. The negative greyscale representation of the combined spectra along the E–W length marked in Fig. 2 is shown. The various nebular emission lines and airglow lines (ag) are identified. The feature above the \([\text{N} \text{II}] \, 6584 \text{Å}\) profiles is an optical ‘ghost’
Figure 8. Various line profiles from the same ≈ 60 arcsec length of the E–W slit shown in Fig. 2 are shown. These extractions were for this length centred 32 arcsec E of the central star to permit a sufficient signal to noise ratio to be achieved for the faint He II 6560 Å profile. If the stellar spectrum is included it is degraded significantly.
Figure 9. A deep NTT image in the light of [O\textsc{iii}] 5007 Å is compared with centroids of the separate velocity components in profiles of the same emission line along the slit position marked in the top panel. The 'inner' [O\textsc{iii}] 5007 Å emitting shell can be seen in the top panel (epoch 2000).
Figure 10. A high contrast, negative greyscale representation of an Hα + [N II] image of the core of NGC 7293. The radial ‘spokes’ that are prominent in the outer regions of the bright nebulosity can be seen to continue faintly to within 30’’ of the central star (epoch 2000).

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Figure 11. The image of the bright helical [N II] 6584 Å emitting rings and the observed E–W and N–S pv arrays of [N II] 6584 Å profiles are simulated using the XSHAPE code. An EW section through the bi-polar model that was used is shown (bottom left box) with a central toroidal ring (viewed here from below). The synthetic image (top left box) should be compared with the observed image (top middle box). Likewise the synthetic pv array to the left of the observed NS one (top right boxes) and the synthetic array below the observed one (bottom right boxes) should be compared. The velocities for the key positions A–D in Fig. 6 match convincingly.