The 3-D shaping of NGC 6741: a massive, fast-evolving Planetary Nebula at the recombination–reionization edge. *

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Abstract. We infer the gas kinematics, diagnostics and ionic radial profiles, distance and central star parameters, nebular photo-ionization model, spatial structure and evolutionary phase of the Planetary Nebula NGC 6741 by means of long-slit ESO NTT+EMMI high-resolution spectra at nine position angles, reduced and analysed according to the tomographic and 3-D methodologies developed at the Astronomical Observatory of Padua (Italy). NGC 6741 (distance≈2.0 kpc, age≈1400 yr, ionized mass M_{ion}≈0.06 M_{⊙}) is a dense (electron density up to 12 000 cm^{-3}), high-excitation, almost-prolate ellipsoid (0.036 pc x 0.020 pc x 0.018 pc, major, intermediate and minor semi-axes, respectively), surrounded by a sharp low-excitation skin (the ionization front), and embedded into a spherical (radius≈0.080 pc), almost-neutral, high-density (n(HI) ≈7×10^{3} atoms cm^{-3}) halo containing a large fraction of the nebular mass (M_{ion} > 0.20 M_{⊙}). The kinematics, physical conditions and ionic structure indicate that NGC 6741 is in a deep recombination phase, started about 200 years ago, and caused by the quick luminosity drop of the massive (M_{∗}=0.66-0.68 M_{⊙}), hot (logT_{e}≈5.23) and faint (log L_{∗}/L_{⊙}≈2.75) post–AGB star, which has exhausted the hydrogen-shell nuclear burning and is moving along the white dwarf cooling sequence. The general expansion law of the ionized gas in NGC 6741, V_{exp}=(km s^{-1})=13×R'' fails in the innermost, highest-excitation layers, which move slower than expected. The observed deceleration is ascribable to the luminosity drop of the central star (the decreasing pressure of the hot-bubble no more balances the pressure of the ionized gas), and appears in striking contrast to recent reports inferring that acceleration is a common property of the Planetary Nebulae innermost layers. A detailed comparative analysis proves that the latter (i. e. “U”-shaped expansion velocity field) is a spurious, incorrect result due to a combination of: (a) simplistic assumption (spherical shell hypothesis for the nebula), (b) unfit reduction method (emission profiles integrated along the slit), and (c) inappropriate diagnostic choice (λ4686 Å of He II, i. e. a thirteen fine-structure components recombination line). Some general implications on the shaping mechanisms of Planetary Nebulae are discussed.

Key words. planetary nebulae: individual: NGC 6741– ISM: kinematics and dynamics

1. Introduction

The sentence by the late Professor Lawrence H. Aller (1994): “A nebula is a three-dimensional structure for which we obtain a two-dimensional projection” fully synthesizes the many, so far unsolved, observational lim-

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At last, the tomographic and 3-D analyses developed at the Astronomical Observatory of Padua (Sabbadin et al. 2004 and references therein) overcame the stumbling block of nebular de-projection, rebuilding the ionic spatial structure, and allowing us a direct comparison of each real, true PN with the current theoretical evolutionary models (Schönberner et al. 1997, Steffen et al. 1998, Marigo et al. 2001), the detailed hydro-dynamical simulations (Icke...
et al. 1992, Frank 1994, Mellema 1997, Perinotto et al. 2004a), and the updated photo-ionization codes (Ferland et al. 1998, Ercolano et al. 2003).

Though the observational starting point is common - i.e., long-slit spectra -, the “philosophy” of tomography is just opposite of the conventional method. In fact, the latter compacts the spectrum along the slit (in practice, it restricts the nebula to a point), and gives mean, integrated results (line flux, expansion velocity, $T_e$, $N_e$, ionization etc.). Vice versa, tomography is based on a pixel-to-pixel analysis of both flux and velocity, and furnishes the bi-dimensional structure (in different ions) of the radial slice of nebula intercepted by the spectrograph slit. Later on, a 3-D rendering procedure combines all tomographic slices and provides the true spatial distribution of the kinematics, physical conditions ($T_e$ and $N_e$), and ionic and chemical abundances at unprecedented accuracy. Tomography needs spectra at high “relative” spatial (SS) and spectral (RR) resolutions (SS=r/Δr, r=apparent radius, $Δr$=seeing; RR=$V_{exp}/ΔV$, $ΔV$=instrument spectral resolution). It is based on the simple consideration that the position, depth and density of each elementary volume within an extended, regularly expanding nebula can be, in principle, derived from the radial velocity, FWHM and flux, respectively, of the corresponding emission.

So far we have studied NGC 40 (Sabbadin et al. 2000a), NGC 1501 (Sabbadin et al. 2000b, Ragazzoni et al. 2001), NGC 6565 (Turatto et al. 2002), NGC 6818 (Benetti et al. 2003) and NGC 7009 (Sabbadin et al. 2004). Here we present the results for NGC 6741.

NGC 6741 (PN G033.8-02.6, Acker et al. 1992) is a compact (main body $≃7’’\times5’’$, halo diameter $≃15’’$; Curtis 1918, Schwarz et al. 1992), high-surface brightness, high-excitation (class 8, Hyung & Aller 1997) PN with a large degree of stratification of the radiation. The powering star is very hot ($\log T_∗ ≥ 5.22$, Pottasch 1981, Pottasch & Preite-Martinez 1983, Heap et al. 1989, Tylenda et al. 1989, Kaler & Jacoby 1989) and faint ($m_V ≃ 19.5$, Pottasch 1981, Tylenda et al. 1989, Kaler & Jacoby 1989, Hyung & Aller 1997).

The [O III] and [N II] apparent morphology of NGC 6741 (sometimes called “Phantom Streak Nebula”) is shown in Figs. 1 and 2 (HST-WFPC2 frames retrieved...
from NASA public archives). Note the vertical (equatorial?) inhomogeneous strip of absorbing knots in the [O III] image of Fig. 1, and in Fig. 2 the roundish halo and the series of weak, radial [O III] rays punching the [N II] skin along and close to the apparent major axis. A multicolor HST reproduction of the nebula is given by Hajian & Terzian at [http://ad.usno.navy.mil/pne/gallery.html](http://ad.usno.navy.mil/pne/gallery.html).

We immediately point out that the optical appearance of NGC 6741, the co-existence of ion species with a large range of ionization potential, IP (from [O I] IP=0 eV to [Ne V] IP=97.1 eV; Aller et al. 1985, Hyung & Aller 1997), and the characteristics of the central star (hot and faint) are suggestive of a recombinating PN, i.e. the star has exhausted the hydrogen-shell nuclear burning and is rapidly fading in luminosity (and temperature); the UV flux being unable to fully ionize the gas, the outer nebular regions recombine, producing the faint halo (Tylenda 1986, Phillips 2000). Under many respects NGC 6741 is very much like NGC 6565 (Turatto et al. 2002).

To deepen the kinematics, physical conditions, ionic and spatial structure, distance and evolutionary status of NGC 6741, we have secured long-slit ESO NTT+EMMI echellograms (spectral range λ33900–7900 Å, spectral resolution λ/Δλ=R=60 000) at nine equally spaced PA, (close to the apparent minor and major axes of NGC 6741, respectively). The richness of physical information contained in the echellograms is illustrated in Figs. 3 and 4, presenting the spectral structure of twelve ionic species (from [O I], IP=0 eV to [Ar V], IP=59.8 eV) at PA=15° and 75° (close to the two extended and faint polar lobes).

We note in passing that the “relative” spectral and spatial resolutions of our echellograms are similar to each other: SS=V_{exp}/ΔV≈3 to 5 ≈ RR−r/Δr. This means that the spatial information of NGC 6741 is as accurate as the kinematical information, and both are close to the lower limit for the tomographic analysis (Ragazzoni et al. 2001). Ergo, the spectral images in Figs. 3 and 4 are affected by non-negligible blurring agents.

Seeing and guiding are the broadening components along the spatial (i.e. vertical) axis; in our case the full width at half maximum, W(spat)_{seeing+guiding}, results to be 0.60″ for PA=15° (Fig. 3), and 0.65″ for PA=75° (Fig. 4). The true, “intrinsic” profile of the nebula has:

\[
W(spat)^2_{\text{intrinsic}} = W(spat)^2_{\text{obs}} - W(spat)^2_{\text{seeing+guiding}}.
\] (1)
Fig. 3. Detailed spectral image of twelve ionic species in NGC 6741 at PA=15° (close to the apparent minor axis), arranged in order of increasing IP (top-left to bottom-right). The original fluxes are multiplied by the factor given in parenthesis, to make each emission comparable with λ5007 Å of [O III]. The blue-shifted gas is to the left. The top-left frame also shows the [O I] night-sky emission at λ6300.304 Å. In the top-right frame the [O II] line at λ7319 Å, partially in blend with λ7320 Å, has been suppressed (for details, see the text and Fig. 5).
Fig. 4. Same as Fig. 3, but for PA=75° (close to the apparent major axis of NGC 6741).
Concerning the velocity (i.e., horizontal) axis, we must take into account:

1. instrumental resolution, corresponding to a Gaussian profile with $W(\text{vel})_{\text{EMMI}} = 5.09 \text{ km s}^{-1}$ (measured in the [O I] night-sky line at $\lambda 6300 \text{ Å}$);

2. thermal motions, generating a Gaussian distribution with $W(\text{vel})_{\text{thermal}} \approx 21.6 \times 10^{-2} \times T_e^{0.5} \times m^{-0.5} \text{ km s}^{-1}$, where $m$ is the atomic weight of the element (Clegg et al. 1999 and references therein); we use the radial $T_e$ profile given in Sect. 7;

3. turbulence, i.e., random, small-scale motions; this is a very uncertain parameter for PNe, whose quantification is deferred to a dedicated paper (in preparation), based on very-high resolution ($R \approx 115,000$) spectra secured with Telescopio Nazionale Galileo (TNG) + SARG on a representative sample of targets. In the present case of NGC 6741, at the moment we can only infer that $W(\text{vel})_{\text{turb}}$ is below 10.0 km s$^{-1}$, as indicated by the sharpness of the spectral images of forbidden lines along the velocity (i.e., x) axis (see Figs. 3 and 4; larger turbulences should produce blurred spectral images of forbidden lines, similar to the H$\alpha$ one). According to the “a posteriori” analysis presented at the end of Sect. 3, in the following we will assume $W(\text{vel})_{\text{turb}} = 3.5 \text{ km s}^{-1}$, in partial agreement with the general results by Neiner et al. (2000), and Gesicki et al. (2003) (but see the caveat in Sect. 3);

4. fine-structure (only for recombination lines); following Clegg et al. (1999), $W(\text{vel})_{\text{fine}} \approx 7.5 \text{ km s}^{-1}$ for H$\alpha$; moreover, we adopt $W(\text{vel})_{\text{fine}} = 5.0 \text{ km s}^{-1}$ for $\lambda 4686 \text{ Å}$ (after suppression of the 20 km s$^{-1}$ blue-shifted tail with the method illustrated in Fig. 5) and $\lambda 6560 \text{ Å}$ of He II, and $\lambda 5876 \text{ Å}$ of He I.

Note that thermal motions and/or fine-structure represent the main broadening factors for recombination lines, whereas instrumental resolution, thermal motions and turbulence are (more or less) equivalent for forbidden lines.

The final broadening along the velocity axis is:

$$W(\text{vel})_{\text{blur}}^2 = \sum_{i=1}^{4} W(\text{vel})_i^2,$$

and the true, intrinsic full-width at half maximum:

$$W(\text{vel})_{\text{intrinsic}}^2 = W(\text{vel})_{\text{obs}}^2 - W(\text{vel})_{\text{blur}}^2.$$

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**Fig. 5.** De-blending procedure for the [O II] $\lambda \lambda 7319$-$7320$ Å doublet (using IRAF packages). Top panel: Image $A$= part of the echellogram (at $\text{PA}=75^\circ$) centered on $\lambda 7319$ Å. Middle panel: Image $B$= part of the echellogram (at $\text{PA}=75^\circ$) centered on $\lambda 7320$ Å. Bottom panel: Image $C = I(7320) - (I(7320)/3.071)$, where 3.071 corresponds to $I(7320)/I(7319)$.

**Fig. 6.** High-contrast [O III] and [N II] line profiles (in logarithmic scale) of NGC 6741 close to the apparent minor and major axes (PA=15° and 75°, respectively) showing the faint halo and red-shifted tail. Same orientation as Figs. 3 and 4.
W(vel)$_{\text{intrinsic}}$ (in km s$^{-1}$) corresponds to the expansion velocity range of the emitting layer; it can be transformed into arcsec by means of the general expansion law of the ionized gas: in NGC 6741 being $V_{\text{exp}}$ (km s$^{-1}$) = 13($\pm$1)$\times$R$''$ (see Sect. 3), we have $W(vel)_{\text{intrinsic}}$ (arcsec) = $[W(vel)_{\text{intrinsic}}$ (km s$^{-1}$)]/13.

Let us consider, for example, the spectral images at PA=15° (Fig. 3). The intrinsic FWHM in both the zvpc and cspl (as defined at the opening of Sect. 3) results to be 0.52'' to 0.72'' (forbidden lines), 0.77'' to 0.95'' (He I), 1.00'' to 1.15'' (He II), and 1.35'' to 1.45'' (H I), thus confirming that:

(a) each emitting region is extremely sharp,
(b) the whole spectral images must be carefully deconvolved: to this end we use the Richardson-Lucy algorithm (Richardson 1972, Lucy 1974), and a point-spread function given by a bi-dimensional gaussian profile characterized by $W(\text{spat})_{\text{seeing+guiding}}$ and $W(vel)_{\text{blur}}$.

So far we have considered the bright main shell of NGC 6741. At lower-flux cuts the faint halo appears (Fig. 6), whose spectral signature supports the recombination hypothesis (note, in particular, the broad, un-tilted halo-emission at PA=15°, and the broad, tilted halo-emission mimicking the kinematics of the main nebula at PA=75°). In fact, according to the current evolutionary models (e.g. Schönberner et al. 1997, Steffen et al. 1998, Marigo et al. 2001, Perinotto et al. 2004a), a PN halo can be:

- an AGB halo, i.e. the low-density envelope of an optically thin PN, directly ionized by the UV flux of the bright central star. It represents the AGB mass-loss in the pre-superwind phase, and expands at the original ejection velocity ($V_{\text{exp}}$ \approx 10-15 km s$^{-1}$), independent on the kinematical field of the main nebula;
- a recombination halo, corresponding to the outer, almost neutral parts of the main nebula, no more reached by the UV flux of a hot central star which has exhausted the H-shell nuclear burning and passed the turnover point in stellar evolution, rapidly fading in luminosity and temperature. The recombining layers essentially retain the general kinematical properties of the main thick nebula (as observed in the halo of NGC 6741).

Fig. 6 also shows the faint red-shifted tail present in the strongest emissions of NGC 6741 at all PA, whose nature (halo? interaction with the ambient ISM? early-AGB wind? instrumental scattered light?) remains unclear.

This preliminary, qualitative description enhances the complexity of NGC 6741 (a common characteristic of all PNe analysed at adequate spatial and spectral resolutions). Before starting a thorough investigation of the kinematical and physical information contained in the spectra, we underline that the general characteristics of NGC 6741 - in particular: (a) nebular compactness, and (b) star weakness (the stellar continuum, generally used as a position marker, is absent in the echellograms) - do make this nebula the ideal target to test the reliability limits of our 3-D reconstruction procedure.

3. The gas spatio-kinematics

According to Sabbadin et al. (2004, and references therein), the overall spatio-kinematical properties of a regularly expanding nebula can be derived by combining the kinematics of the gas projected at the apparent position of the star (the “central star pixel line”, cspl, of the echellograms, common at all PA) with the spatial profile at the systemic radial velocity (the “zero velocity pixel column”, zvpc, at each PA).

Though the stellar continuum is absent in the echellograms of NGC 6741, we obtain a satisfactory cspl-location and zvpc-alignment (within $\pm$0.1'') of the echelle orders thanks to: (a) the central, symmetrical position of the star in the broad-band HST-WFPC2 nebular images, (b) the cspl- and zvpc-calibration given by the continuum spectrum of the central star of NGC 7009 (observed at the same night, and with the same instrumental configuration).

The peak separations in the cspl of NGC 6741, $2V_{\text{exp}}$, are contained in Table 1 (last column), where ions are put in order of increasing IP. Typical errors are 1.0 km s$^{-1}$ for the strongest forbidden emissions (like $\lambda$4959-5007 A of [O III] and $\lambda$6548-6584 A of [N II]) to 2.0 km s$^{-1}$ for the faintest ones (in particular, $\lambda$6312 A of [S III], $\lambda$4711-4740 A of [Ar IV] and $\lambda$6435-7005 A of [Ar V]).

Concerning the zvpc at the nine PA of NGC 6741, the intensity peak separations, $2R_{\text{zvpc}}$, in the different ionic species are listed in Table 2.

To assemble the kinematical results of Table 1 and the spatial results of Table 2 we can follow two ways:

(I) Search for the PA with $R_{\text{zvpc}} \approx R_{\text{cspl}}$. Let us assume for the main shell of NGC 6741 the most general spatial structure, i.e. a tri-axial ellipsoid with axes a, b and c. At PA = 75° to 115° (close to the apparent major axis, Fig. 4) the line-tilt indicates that the observer is not aligned with the major axis, and the overall emission structure (suggestive of a dense equatorial torus + two faint polar lobes) excludes the oblate (a=b) ellipsoid hypothesis. Moreover, the absence of line-tilt at PA=15° (perpendicular to the apparent major axis, Fig. 3) means that either the minor axis of the ellipsoid is close to PA=15°, or the intermediate axis of the ellipsoid is close to PA=15°, or the ellipsoid is prolate (b=c). In all cases we conclude that, in first approximation, $R(\text{minor axis}) \approx R(\text{intermediate axis}) \approx R_{\text{zvpc}}(\text{PA=15°}) \approx R_{\text{cspl}}$, providing (through Tables 1 and 2): $V_{\text{exp}}$ (km s$^{-1}$) = 13($\pm$2)$\times$R$''$. 
Table 1. Peak separation in the cspl of NGC 6741

| Ion   | IP range (eV) | Wilson (1950) | Robinson et al. (1982) | this paper |
|-------|---------------|---------------|------------------------|------------|
| [O I] | 0.0-13.6      | -             | -                      | 55.1       |
| [S II]| 10.4-23.3     | -             | -                      | 54.0       |
| [O II]| 13.6-35.1     | 44.2          | -                      | 53.7       |
| H I   | ≥13.6         | -             | -                      | 44.0       |
| [N II]| 14.5-29.6     | 42.1          | -                      | 53.5       |
| [S III]| 23.4-34.8   | -             | -                      | 48.2       |
| He I  | 24.6-54.4     | -             | -                      | 48.0       |
| [Ar III]| 27.6-40.7  | -             | -                      | 47.6       |
| [O III]| 35.1-54.9   | 41.6          | 42                     | 46.1       |
| [Ar IV]| 40.7-59.8   | -             | -                      | 33.7       |
| [Ne III]| 41.0-63.4  | -             | -                      | 48.2       |
| N III | 47.4-77.5     | -             | -                      | 40.0       |
| He II | ≥54.4         | -             | -                      | 34.0       |
| [Ar V]| 59.8-75.0     | -             | -                      | 25.0       |
| [Ne V]| 97.1-126.2    | 0.0:          | -                      | -          |

Fig. 7. Nebular tomography vs. spectral image connection. In this example we use the [O III] spectral images of NGC 6741 at PA=75° and PA=15° (same orientation as Figs. 3 and 4). Left panel: tomographic map of the nebular slice intercepted by a spectrograph slit aligned with the apparent major axis of an ellipsoidal PN denser at the equator than at the poles; a and b are the polar and equatorial axes, respectively, of the elliptical nebular slice. Central panel: spectral image of the nebular slice shown in the left panel; a’ and b’ are the polar and equatorial axes, respectively, of the spectral image. Right panel: [O III] tomographic reconstruction of NGC 6741 at PA=15°. See the text for details.

(II) Spectral image deformation along the major axis.

Let us consider a generic, expanding ($V_{\text{exp}} \propto R$) tri-axial ellipsoid denser in the equatorial region than at the poles, seen at an intermediate direction. A spectrograph slit aligned with the apparent major axis intercepts the radial slice of nebula shown in Fig. 7 (left panel): an ellipse with polar axis a and equatorial axis b, perpendicular to each other. The corresponding spectral image is an ellipse too (Fig. 7, central panel), but deformed (with respect to the tomographic map) by the telescope + spectrograph characteristics. Note that:
Table 2. Peak separation in the zvpc at the nine PA of NGC 6741

| Ion   | 2r_{zvpc} (arcsec) | PA=15° | 35° | 55° | 75° | 95° | 115° | 135° | 155° | 175° |
|-------|---------------------|--------|-----|-----|-----|-----|------|------|------|------|
| [O I] | 4.3 4.6 5.7 7.3 6.8 7.1 6.1 5.6 4.6 |
| [S II]| 4.1 4.5 5.5 7.1 6.6 6.9 6.0 5.5 4.4 |
| [O II]| 4.0 4.3 5.2 6.6 6.5 6.6 5.8 5.2 4.3 |
| HI    | 3.5 3.5 4.1 6.0 6.0 6.0 5.2 4.5 3.8 |
| [N II]| 4.1 4.4 5.4 6.8 6.5 6.5 6.5 5.9 5.2 4.4 |
| [S III]| 3.6 4.1 4.6 6.0 5.7 6.0 5.5 4.6 3.9 |
| He I  | 3.8 4.0 4.5 6.2 5.7 6.0 5.5 4.6 4.0 |
| [Ar III]| 3.7 3.8 4.5 5.9 5.0 6.0 5.5 4.6 4.1 |
| [O III]| 3.6 3.7 4.4 5.3 4.7 5.5 5.0 4.4 3.8 |
| [Ar IV]| 2.7 3.2 3.6 3.9 3.9 5.3 4.5 3.4 3.1 |
| [Ne III]| 3.6 3.5: 4.0 4.5 5.0: 5.6: 5.0 4.0 3.6 |
| N III | 3.0: 3.1: 3.6: 4.0: 4.2: 5.1: 4.4: 3.4: 3.2: |
| He II | 2.6 2.9 3.4 3.8 3.9 5.0 3.9 3.2 2.9 |
| [Ar V]| 2.3 2.6 2.8 3.0 3.5: 4.0: 3.6 3.0 2.7 |

- the polar axis (a') and the equatorial axis (b') of the spectral image are no more perpendicular to each other,
- the original tomographic map (Fig. 7, left panel) can be obtained by means of a simple compression of the spectral image (Fig. 7, central panel) along the x (i.e. velocity) axis, till having a'\perpendicular b'.

In practice, and reversing the foregoing procedure, we compress the [O III] spectral image of NGC 6741 at PA=75° (Fig. 7, central panel) by a factor 1.60 along the x axis, thus correcting for the spectral deformation introduced by NTT+EMMI on the nebular slice intercepted by the slit, and obtaining:
- the tomographic map shown in Fig. 7 (left panel),
- the expansion law \( V_{\text{exp}}(\text{km s}^{-1}) = 13(\pm 1) R'' \).

This is the same law given by method (I). In fact, the compression factor along the x axis being the same at all PA, we can repeat the procedure for the [O III] spectral image of NGC 6741 at PA=15° (close to the apparent minor axis; Fig. 3), thus recovering the tomographic map shown in the right panel of Fig. 7, i.e. an almost circular ring with \( R_{\text{zvpc}}(\text{PA}=15°) \approx R_{\text{espl}}, \)

QED! ²

The detailed cspl–zvpc relation for NGC 6741 at PA=15°, shown in Fig. 8, indicates that:

a) on the whole, the ionized gas follows Wilson's law: the high-excitation zones expand more slowly than the low-excitation ones, and a positive correlation exists between the expansion velocity and the size of the monochromatic image (Wilson 1950);

b) the range of both \( 2r_{\text{zvpc}} \) and \( 2V_{\text{exp}} \) is quite large (2.3 to 4.3 arcsec and 25.0 to 55.1 km s\(^{-1}\), respectively), suggesting a broad radial density profile and large stratification of the radiation;

c) the general expansion law, \( V_{\text{exp}}(\text{km s}^{-1}) = 13 R'' \), fails in the innermost, highest ionization layers marked by the [Ar V] emissions: they expand slower than expected.

Point c) is quite peculiar among PNe, and deserves some comments. Deceleration is present (and clear) in both the \( \lambda 6435 \) A and \( \lambda 7005 \) A [Ar V] lines at all PA of NGC 6741 (except along and close to the apparent major axis, where the open-ended structure of the [Ar V] spectral image prevents any conclusion; see Fig. 4, lower-right panel), whereas no evidence of deceleration appears in other high ionization species, like He II (due to the blurred emissions) and N III (\( \lambda 6460 \) A is too faint). Though a detailed spatio-kinematical study at even higher ionization stages appears indispensable - for example in the forbidden line of Ne\(^+\) (\( \lambda 3425 \) A, IP=97.1 eV) at \( \lambda 3425 \) A (which is outside our spectral range) - a support to the deceleration hypothesis comes from the classical work by Wilson (1950), who obtained \( V_{\text{exp}}[\text{Ne V}] \approx 0 \) km s\(^{-1}\) (quite uncertain).

We believe NGC 6741 is the first PN showing clear evidences of deceleration in the highest ionization layers (the second candidate being IC 418: a preliminary analysis of our NTT+EMMI echellograms, taken at six PA, suggests the probable presence of infalling gas).

Vice versa, recent results by Gesicki & Zijlstra (2003, 3 PNe) and Gesicki et al. (2003, 14 PNe) - based on high-resolution emission profiles integrated along the slit, and spherical shell hypothesis for the emitting gas - indicate that acceleration is a quite common property of the PN innermost layers (i.e. “U”-shaped expansion profile), due to the dynamical contribution by the shocked, hot wind from the central star. Gesicki & Zijlstra (2003) adopted

¹ This visual effect can be seen by rotating Fig. 7 around the y axis.
² quod erat demostrandum; Latin for: which was to be proved.
λ4686 Å of He II as diagnostic of the high-ionization kinematics, whereas Gesicki et al. (2003) used λ5007 Å of [O III] (in a few cases λ6560 Å of He II).

The following caveats are in order:
1) the spherical shell assumption is wide of the mark;
2) λ5007 Å of [O III] (IP range 35.1 to 54.9 eV) is a poor diagnostic of the highest ionization strata (except for very-low excitation PNe);
3) the recombination lines of hydrogen and helium do suffer severe blurring effects (thermal motions, fine-structure and expansion velocity gradient across the nebula combined with the small number of ionization stages of H and He), introducing spurious kinematical results.

In particular, λ4686 Å, He II Paschen α, consists of thirteen fine-structure components spread in the λ4685.377–4685.918 Å range (corresponding to ΔV=34.6 km s\(^{-1}\)), with a strong blue-shifted tail (see Figs. 3 and 4). In the case of λ6560 Å, He II Pickering β, the fine-structure components are even nineteen, covering the λ6559.769–6560.209 Å spectral range (ΔV=20.1 km s\(^{-1}\)).

To further test this point, let us consider the emission line profiles integrated along the slit of NGC 6741 at PA=15°. The results for λ4686 Å and λ6560 Å of He II, and the ionic sequence of argon - [Ar III] at λ7135 Å, [Ar IV] at λ4740 Å and [Ar V] at λ7005 Å - are shown in Fig. 9; they confirm that:
- a) spherical symmetry is a simplistic assumption,
- b) the He II recombination lines fail to fit the well-defined stratification of both the radiation and expansion present in the ionic sequence of argon, FWHM(He II, IP range >54.4 eV) being intermediate between FWHM([Ar III], IP range 27.6-40.7 eV) and FWHM([Ar IV], IP range 40.7-59.8 eV), whereas, according to the detailed kinematical results presented in this section, we would expect FWHM(He II) ≤ FWHM([Ar IV]) << FWHM([Ar III]).

The same discrepancy occurs when considering either more parameters (like full-width at 10% maximum flux), or different ionic sequences, or further PA of NGC 6741, or other PNe of our sample.

A direct confirmation of the misleading kinematical results - in particular, the high-velocity of the innermost layers - provided by the combination (spectral profile of recombination lines integrated along the slit) + (spherical symmetry assumption) comes from a comparative analysis of the emission line profiles contained in Gesicki & Zijlstra (2003) and Gesicki et al. (2003): in all cases (17 PNe) the forbidden lines of the ionic species with the highest IP, also show the sharpest emission profile (as expected for a simple, positive V\(_{\exp}\) vs. radius relation).

All this questions the general validity of the spatio-kinematical studies based on the spherical symmetry assumption and/or spectral profiles of recombination lines integrated along the slit, and weaken (or even cancels) the reliability of their results on turbulence, radial kinematics, matter distribution and ionization, whose quantification needs detailed studies at high spatial and spectral resolutions.

Let us go on. Fig. 10 (multi-color map only in the “free” electronic version of the paper, for lack of funds) shows the complete velocity field at the nine observed PA of NGC 6741. We select He II, [O III] and [N II] as markers of the high, medium and low-excitation regions, respectively. These position–velocity (P–V) maps are relative to the systemic heliocentric velocity of the nebula, V\(_{\text{rad}}\)\(=\)+39.6(±1.0) km s\(^{-1}\), corresponding to V\(_{\text{LSR}}\)\(=\)+56.4(±1.0) km s\(^{-1}\), and are scaled (along the x axis) according to V\(_{\exp}\)\(=\)13×R\(^{0.7}\), i.e. they reproduce the tomographic maps of the nebular slices covered by the spectrograph slit.

Fig. 10 highlights the kinematical complexity and large stratification of the radiation within NGC 6741. The main nebula consists of an almost-prolate ellipsoid (a ≈ 7.4′′, a/b ≈ 1.8, a/c ≈ 2.0), whose major axis (projected at PA≈95°) forms an angle of 55(±3)° with the line of sight: on the whole, the eastern part of the nebula is approaching the observer, and the western part receding.

All this throws new light on two specific fields: (I) nature of the curious skip of absorbing knots present in Fig. 1 (upper panel), and (II) turbulent motions.

**I) Skip of absorbing knots:** the central location, orientation (vertical), and light curvature (concavity towards East) are suggestive of an inhomogeneous belt of neutral matter (gas + molecules + dust) embedding the dense ionized gas of the equatorial regions. The amount of circum-nebular neutral gas can be estimated from the
(II) turbulent motions. In Fig. 10 the tomographic map close to the apparent minor axis (i.e. at PA=15°) being almost circular and quite homogeneous, we can assume $W_{\text{spat}}^{\text{intrinsic}}(\text{zvpc at PA}=15°) \approx W_{\text{vel}}^{\text{intrinsic}}(\text{cspl})$, thus inferring $W_{\text{vel}}^{\text{turb}}$ (through Eqs. (1) to (3), $V_{\text{exp}}(\text{km } s^{-1}) = 13 \times R''$, and the $T_e$ radial profile given in Sect. 7.1). We overlook the recombination lines of hydrogen and helium (dominated by thermal motions and/or fine-structure), and consider the strongest forbidden lines. The analysis of $\lambda 6300$ (O I), $\lambda 6713$ (S II), $\lambda 6584$ (N II), $\lambda 7135$ (Ar III), and $\lambda 5007$ (O III) provides $W_{\text{vel}}^{\text{turb}} = 3.5(\pm 2.0) \text{ km } s^{-1}$, with no evident relation to the ionization degree. Thus, in spite of the crude assumptions and wide uncertainties, we conclude that turbulent motions in NGC 6741 are quite modest.

4. The absorption (interstellar + circum-nebular)

In general, the observed line intensities must be corrected for absorption according to:

$$\log \frac{I(\lambda)_{\text{corr}}}{I(\lambda)_{\text{obs}}} = k_\lambda \times c(H\beta)_{\text{tot}},$$

where $k_\lambda$ is the extinction coefficient (Seaton 1979), and $c(H\beta)_{\text{tot}}$ the logarithmic extinction at H\beta caused by the local absorbing matter.

Intensity scans in the neighbourhood of the deepest knots provide $F_{\text{interactive}}(\lambda)/F_{\text{on-the-knot}}$ up to 1.4 (±0.1), i.e. $c(H\beta)_{\text{circum-nebular}}$ up to 0.18 (±0.03). Assuming a “normal” gas-to-dust ratio (Spitzer 1978, Bohlin et al. 1978) and $c(H\beta)_{\text{circum-nebular}} = 1.48 \times E(B-V)$ (Acker 1978), we have:

$$n(H\text{I}) = \frac{4.8 \times 10^{21} \times E(B-V)_{\text{circum-nebular}}}{\Delta l},$$

where $n(H\text{I})$ is the H I density (atoms cm$^{-3}$), and $\Delta l$ the radial thickness (cm) of the absorbing layer. For $D=2000$ pc (see Sect. 5) and $\Delta l = [r(\text{halo}) - r(\text{main nebula at }PA=15°)]/2 \approx 2.0''$ (from Figs. 1 and 2), we obtain an indicative value of $n(H\text{I}) \simeq 7 \times 10^3$ atoms cm$^{-3}$. Such a high density of the circum-nebular matter in NGC 6741 is a further support to the recombination hypothesis outlined in the previous sections.

In the case of NGC 6741, which is optically thick, we apply the $H\alpha$ analysis of the whole spectral image, as introduced by Turatto et al. (2002). Fig. 11 shows the $F(H\alpha)/F(H\beta)$ isophotal contours superimposed to the H\beta spectral image for three representative PA of NGC 6741: at PA=15° (close to the apparent minor axis; untilted H\beta spectral image) $F(H\alpha)/F(H\beta)$ increases outwards along the spatial (i.e. $y$) axis, peaking beyond the top of the H\beta flux. At PA=55° (intermediate PA; tilted H\beta spectral image) the $F(H\alpha)/F(H\beta)$ raise along the $y$ axis is overwhelmed by the broad maximum at S-W of the nebular centre (at the expected position of the absorbing belt visible in Fig. 1, upper panel). The same occurs at PA=75° (close to the apparent major axis; tilted H\beta spectral image), where $F(H\alpha)/F(H\beta)$ peaks at W-SW of the centre, in correspondence of the equatorial absorbing belt.

Summing up the $H\alpha/H\beta$ intensity distribution at the nine observed PA of NGC 6741, we infer that:

a) $c(H\beta)_{\text{interstellar}} = 0.95 (\pm 0.05)$,
Fig. 10. Combined position–velocity maps in the nine observed PA of NGC 6741 at high (He II), medium ([O III]) and low ([N II]) excitation (multi-color maps in the electronic version of the paper; blue=He II, green=[O III], and red=[N II]), scaled according to the relation $V_{\text{exp}}$ (km s$^{-1}$)=$13 \times R''$. The orientation of these tomographic maps is the same of Figs. 3 and 4.

b) $c(H\beta)_{\text{circum-nebular}}$ is 0.10 ($\pm$0.03) in the central region of the nebular image (out of the equatorial absorbing belt), and raises up to 0.20 ($\pm$0.05) within the equatorial absorbing belt, and at the edge of the ionized zone.

Moreover, a modest decrease of $F(H\alpha)/F(H\beta)$ in the innermost regions (out of the equatorial absorbing belt) is suggestive of a local increase of $T_e$.

Last, an indicative value of the total neutral mass embedding the ionized nebula (through Eq. (5) and using simple geometrical considerations) is $M_{\text{neutral}} \simeq 0.20$ ($\pm$0.05) $M_\odot$.

Though the small angular size prevents a deeper analysis, these results do represent the umpteenth sign of the complex structure and peculiar evolutionary phase of NGC 6741, and will be a precious support in the determination of the topical parameter, i. e. distance.
Fig. 11. $F(\text{H}\alpha)/F(\text{H}\beta)$ isophotal contours superimposed to the $\text{H}\beta$ spectral image for three representative PA of NGC 6741. Left panel: PA=15° (close to the apparent minor axis); central panel: PA=55° (intermediate direction); right panel: PA=75° (close to the apparent major axis). Same orientation as Figs. 3 and 4. The isophotal contours cover the range 5.20 (the outermost) to 7.60, with a constant step of 0.30.

5. The nebular distance, size and age

The “statistical” distance of NGC 6741, provided by two dozen catalogues using different methods and assumptions, is:

$$<D>(\text{Shklovsky}) \approx 3300(\pm 1000) \text{ pc}$$
$$<D>(\text{ionized mass–radius relation}) \approx 1500(\pm 700) \text{ pc}$$
$$<D>(\text{other methods}) \approx 2000(\pm 1000) \text{ pc},$$

where $<D>(\text{Shklovsky})$ represents an upper limit of the true distance, NGC 6741 being an optically thick, ionization bounded PN.

Individual values reported in the literature are: 1300 pc (nebular radial velocity combined with the circular law of galactic rotation; Acker 1978), 2100 pc (Acker 1978) and 1400 pc (Pottasch 1983) (both based on the large-scale galactic interstellar absorption map by Lucke 1978), and 1500 pc (color-excess vs distance relation for early-type stars within 1.5° of the nebula; Kaler & Lutz 1985).

We tried to determine the nebular parallax by combining the expansion velocity field with the angular expansion measured in first- and second epoch HST-WFPC2 frames. The NASA public archives contain 21 images of NGC 6741, taken at two epochs separated by 2.97 years (programs GO 7501 and GO 8773; P. I. Arsen Hajjian). The [O III] and [N II] multiple exposures (WFPC2 central planetary camera, PC; pixel size=0.0455 arcsec) were co-added, corrected for optical distortions, aligned and rotated using IRAF packages (Reed et al. 1999; Palen et al. 2002).

No apparent image-shift is detected, i. e. image-shift $\leq \frac{1}{2}$ pixel, and $\frac{\text{d} \theta}{\text{d} t} \leq 8 \times 10^{-3}$ arcsec yr$^{-1}$. For an optically thin, fully ionized PN this implies $D \geq 1400$ pc, being:

$$D(\text{pc}) = \frac{0.211V_{\exp}(\text{km s}^{-1})}{\frac{\text{d} \theta}{\text{d} t} \text{ (arcsec yr}^{-1})}. \quad \text{(8)}$$

But NGC 6741 is optically thick (probably recombining), and Eq. (8) cannot be applied, since in this case we should compare the expansion velocity of the ionized gas with the angular expansion of the ionization front. To be noticed that, in the limit case of a nearby nebula in a very deep recombination phase, we even expect a detectable contraction of the ionization front. Thus, we infer (a mere speculation, at the moment) that $D(\text{NGC 6741}) \geq 1500$ pc, and/or the nebula is at the end of the recombination phase (or at the reionization start).

As a last chance for the nebular distance determination, we decided to enrich (and sharpen, if possible) the broad color-excess vs. D relation given by Kaler & Lutz (1985) with the recent bibliographic reports. The scanning of the NGC 6741 neighbourhood with the SIMBAD facilities of CDS (Centre de Données astronomiques de Strasbourg) gave fruitful results; besides two dozen (low-weight) field stars with accurate photometry and spectral type (in most cases the luminosity class is absent; we assume a luminosity class V), we have identified two important distance markers:

- the open cluster OCL 88 (at an apparent distance of 15.4’ from NGC 6741), characterized by E(B-V)=1.0
and D=3000 pc (Sagar & Griffiths 1998, and referenced therein),
- the classical Cepheid V336 Aql (apparent distance from NGC 6741=37.0’), with log P=0.8636 days,
< mV>=9.875, E(B-V)=0.61–0.64, and D=1800–2100 pc (Pel 1976, Feast & Whitelock 1997, Metzger et al. 1998, Berdnikov et al. 2000).

The improved E(B-V) vs. D relation in the direction of NGC 6741 is shown in Fig. 12: the interstellar absorption starts at D≈ 200–300 pc, and gradually increases up to 3000 pc (and beyond). This is in partial disagreement with the literature reports. We recall that NGC 6741 is within the Aquila-Scutum cloud, a galactic region characterized by a high, quite uniform star density, suggestive of a low obscuration. According to Forbes (1985), it shows an almost immediate climb at A_V=2.3 mag. within 300 pc; beyond this distance, there is little or no increase of extinction out to D=6000 pc.

To test this point, let us consider the four more PNe projected within the Aquila-Scutum cloud (at an apparent distance from NGC 6741 lower than 90’). They are CBSS 3, K 3-19, M 1-66 and K 3-20 (we reject a fifth object, Sp 2-151, because of the unreliable line intensities - in particular F(\text{H}α)/F(\text{H}β)≈1.0 - and peculiar spectral-type A for the exciting star reported by Acker et al. 1992, probably due to the partial blending with a relatively bright, m_γ≈13.0, field star). The four selected PNe in the Aquila-Scutum cloud do have 1.5≤c(\text{H}β)≤2.2 (line intensities by Acker et al. 1992, and Cappellaro et al. 1994, for T_e=10^4 K and N_e=2×10^3 \text{cm}^{-3}), i.e. 3.2≤A_V≤4.7, and, using the obscuration law by Forbes (1985), D> 6000 pc for all four nebulae.

The last result appearing quite improbable, and, in our opinion, questionable, in the following we will adopt the color-excess vs. distance relation shown in Fig. 12. It provides D(NGC 6741) = 2000 (±300) pc.

The linear size of the main nebula is 0.036 pc x 0.020 pc x 0.018 pc (major, intermediate and minor semi-axes, respectively), whereas both the spherical recombining halo and the [O III] rays punching the [N II] skin close to the apparent major axis extend up to 0.080 pc.

The “kinematical” age of NGC 6741, t_{\text{kin}}=\frac{R}{V_{\text{exp}}}, is about 750 years, and the “true” age t_{\text{true}}≈2R/\left[\frac{V_{\text{exp}}(\text{today})+V_{\text{exp}}(\text{AGB})}{2}\right]≈ 1400 years.

Summing up: NGC 6741 is a very young, compact, high surface brightness (i.e. dense) PN. The combination of: (a) high excitation (up to [Ne V]) of the innermost layers, (b) low ionization skin, and (c) almost neutral, large density halo, is indicative of a very hot central star at low luminosity. A deep analysis of the powering engine is in order.

6. The central star parameters

The HST-WFPC2 frames of NGC 6741 taken through the broad-band filter F555W (central wavelength=5407 Å, bandwidth=1236 Å) provide m_V=20.09 (±0.05), where the un-known star color is the main source of inaccuracy. Previous ground-based estimates reported in the literature are: 19.5 (Pottasch 1981), 17.6 (Tylenda et al. 1989), 19.16 (Kaler & Jacoby 1989) and 19.26 (Hyung & Aller 1997) for m_V, and >20.2 (Gathier & Pottasch 1988) and 18.2 (Tylenda et al. 1989) for m_γ.

The H I and He II Zanstra temperatures are given by the stellar magnitude, combined with both the total Hβ nebular flux, log F(\text{H}β)_{\text{obs}}=-11.32 (±0.03) mW·m^-2 (Kaler & Lutz 1985, Tylenda & Jacoby 1989, Kaler et al. 1991, Cahn et al. 1992, this paper), and the flux ratio F(\text{X4686} Å)/F(\text{H}β)=0.40 (±0.03) (Aller at al. 1985, Kaler & Jacoby 1989, Hyung & Aller 1997, this paper).

We obtain log(T_2H I)=5.33 (±0.07) and log(T_2\text{He II})=5.23 (±0.07), thus confirming the peculiarity already reported by Heap et al. (1989) and Hyung & Aller (1997), i.e. the Zanstra discrepancy is reversed. T_2H I>T_2\text{He II} is a typical signature of recombining PNe, e.g. NGC 6565 (Turatto et al. 2002), where the ionization and thermal structure are out of equilibrium, and the recombination processes dominate. These are faster for the higher-ionization species (Tylenda 1986, Stasinska 1989, Marten & Szczepan 1997); thus, in the following, we will adopt T_2≈T_2\text{He II}<T_2H I.

The stellar luminosity (using D=2000 pc, and the bolometric corrections by Schönberner 1981) results to be log L_*/L_⊙=2.75 (±0.15).

The high temperature and low luminosity of the star, added to the short nebular age, suggest that the stellar mass, M_*, is larger than the average value (≈0.60 M_⊙) of
the PNe nuclei. According to the evolutionary tracks by Schönberner (1981, 1983), Iben (1984), Wood & Faulkner (1986), Blöcker & Schönberner (1990), Vassiliadis & Wood (1994) and Blöcker (1995), the 0.66-0.68 $M_\odot$ post-AGB star of NGC 6741 has recently (a few hundreds years ago) exhausted the hydrogen–shell nuclear burning, and is fading along the white dwarf cooling sequence.

To be noticed: the early luminosity decline of the star was very fast (and caused the nebular recombination), but later it gradually slowed, so that we cannot exclude that, at present, the gas has reached (or even passed) the contraction-expansion equilibrium condition, $(1/3)\times(d(lnL_*)/dt)=-2/t_{\text{kin}}$ in the classical Strömgren model, thanks to the matter dilution due to expansion.

New input will come from the nebular physical conditions, radial ionization structure and photo-ionization model.

7. The nebular parameters

7.1. Physical conditions and ionized mass

Following Sabbadin et al. (2004, and references therein), the radial profile of the physical conditions is given by the zvpc, which is independent on the expansion velocity field, since it represents the gas in the plane of the sky, whose motion is tangential. For $T_e$ we use the classical diagnostic line ratios of ions in p$^2$ and p$^4$ configurations ($\lambda5007/\lambda4363$ Å of [O III] and $\lambda5684/\lambda5755$ Å of [N II]; Aller 1984, Osterbrock 1989), whereas $N_e$ comes from both diagnostic line ratios of ions in p$^3$ configuration ($\lambda6717/\lambda6731$ Å of [S II] and $\lambda4711/\lambda4740$ Å of [Ar IV]), and the absolute $H\alpha$ flux distribution.

The main limitation is connected to the NGC 6741 compactness, large stratification of the radiation, and weakness of the [N II] aural line and the [S II] and [Ar IV] doublets: $T_e$[N II], $N_e$[S II] and $N_e$[Ar IV] can be derived only at (or close to) the intensity peak of the corresponding emission.

Moreover, the large $H\alpha$ broadening implies a complex deconvolution for instrumental resolution plus thermal motions plus fine-structure (see Sect. 2), lowering the accuracy of the $F(H\alpha)_{\text{zvpc}}$ and $N_e(H\alpha)$ profiles. Thus, according to Benetti et al. (2003), $F(H\alpha)_{\text{zvpc}}$ and $N_e(H\alpha)$ are also obtained from the radial ionization structure relative to O$^+$ (Sect. 7.2) and the fair assumption $O/H=constant$ across the nebula; at each position:

$$F(H\alpha)_{\text{zvpc}} \propto \frac{H}{O} \times f(T_e) \times \text{icf(O}^+\text{)},$$

with $\text{icf(O}^+\text{)}=\frac{O}{O^+}=\text{ionization correcting factor}.$

For the internal, high-excitation regions $\text{icf(O}^+\text{)}$ comes from the ionization structure of helium (Seaton 1968, Benetti et al. 2003):

$$\text{icf(O}^+\text{)}_{\text{inner}} = 1 + \frac{0.3 \times H e^+}{H e^+};$$

for the external, low-excitation layers we adopt:

$$\text{icf(O}^+\text{)}_{\text{outer}} = 1 + \frac{O^0}{O^+} + \frac{O^+}{O^{++}},$$

which includes the ionization effects produced by the resonant charge-exchange reaction $O^+ + H^0 \rightarrow O^0 + H^+$; according to Osterbrock (1989) and Stancil et al. (1999), in the outermost nebular regions $H^0/H^+ \approx 0.83 \times (O^0/O^+)$. Moreover (Sabbadin et al. 2004),

$$N_e(H\alpha) \propto \frac{1}{T_e^{-0.47}} \times \left(\frac{F(H\alpha)_{\text{zvpc}}}{\epsilon_1 \times D}\right)^{1/2},$$

where $D$ is the (known) distance, and $\epsilon_1$ the (unknown) “local filling factor”, i.e. the fraction of the local volume actually filled by matter with density $N_e$.

A comparative analysis gives quite satisfactory results: the $N_e(H\alpha)$ profiles obtained in the two ways differ by less than 5% everywhere, except in the faint, innermost regions, where the discrepancy raises up to 10%. In the following we will adopt $N_e(H\alpha)$ given by $F(\lambda5007\,\AA)_{\text{zvpc}}$ and Eqs. (9) to (12).

Fig. 13 shows the resulting radial distribution of the physical conditions in NGC 6741 at PA=15° and PA=75° (close to the apparent minor and major axes, respectively).

The radial trend of $T_e$[O III] is common at all PA: $\geq 15000$ K in the weak innermost regions, rapidly decreasing outward down to 12000 K in the densest layers, and more or less constant further out (uncertain). $T_e$[N II] is systematically lower than $T_e$[O III]. All this is in quantitative agreement with the results by Hyung & Aller (1997) and Pottasch et al. (2001).

$N_e$ presents a broad, asymmetric bell-shape profile with peaks up to 12000 ($\pm 1000$) cm$^{-3}$ close to the minor axis, and 6000-8000 ($\pm 500$) cm$^{-3}$ close to the major axis. Note that, in spite of the high density peaks - causing strong collisional de-excitation of the [S II] $\lambda6717$ Å line - we have $N_e$[O III]$\approx N_e$($H\alpha$), i.e. the local filling factor is $\epsilon_1\approx 1$, being $N_e$[S II]$\propto \epsilon_1^{1.5} \approx N_e$($H\alpha$) (Aller 1984, Pottasch 1984, Osterbrock 1989).

$N_e$[Ar IV] is systematically lower than $N_e$[S II] adopting the electron impact excitation rates by Keenan et al. (1997), whereas $N_e$[Ar IV]$\approx N_e$[S II] for earlier collisional rates (for example, Aller 1984).

Concerning the halo, $N_e$ peaks at the inner edge ($\approx 1000 - 1500$ cm$^{-3}$), and decreases outwards.

Recent density determinations (mean values integrated over the slit) reported in the literature for NGC 6741 are: $N_e$(different ions)=$6300$ cm$^{-3}$ by Hyung & Aller (1997), $N_e$[O III]=$6000$ cm$^{-3}$, $N_e$[O II]=$8500$ cm$^{-3}$, $N_e$[Cl III]=$9000$ cm$^{-3}$ and $N_e$[Ar IV]=$5500$ cm$^{-3}$ by Pottasch et al. (2001), and $N_e$[Cl III]=$4470$ cm$^{-3}$, $N_e$[Ar IV]=$6610$ cm$^{-3}$ and $N_e$[52µm/88µm]=$2880$ cm$^{-3}$ by Liu et al. (2001).

The ionized mass of NGC 6741, obtainable from the observed $N_e$ spatial distribution, the Hβ flux, and the radio flux (Aller 1984, Pottasch 1984, Osterbrock 1989, and...
Fig. 13. Radial distribution of the physical conditions ($T_e$ and $N_e$) at two selected directions of NGC 6741. Upper panel: the zvpc at PA=15° (close to the apparent minor axis); lower panel: the zvpc at PA=75° (close to the apparent major axis). Left ordinate scale: $T_e$[O III] (continuous line) and $T_e$[N II] (empty squares). Right ordinate scale: $N_e$(H$\alpha$) for D=2000 pc (dotted line), $N_e$[S II] (empty circles), and $N_e$[Ar IV] (filled circles).

Turatto et al. 2002), results to be $M_{\text{ion}} \simeq 0.06(\pm 0.02) M_\odot$, i.e. much lower than the mass of the external, neutral cocoon, $M_{\text{neutral}} \simeq 0.20 (\pm 0.05) M_\odot$ (see Sect. 4), thus confirming the peculiar evolutionary phase of our nebula.

To be noticed: the relatively high $N_e$ of the halo implies a quite recent recombination start, no more than 200 years ago. In fact, the $N_e$ depletion rate for recombination is:

\[
\frac{dN_e}{dt} = -\alpha_B \times N_e \times N(H^+),
\]

with $\alpha_B$=effective recombination coefficient. Assuming $N_e \simeq N(H^+)$ and $T_e=12000$ K, and neglecting the recombination delay due to expansion, we obtain:

\[
N_e(0) = N_e(t)/[1 - 8.2 \times 10^{-6} \times t \times N_e(t)],
\]

where $N_e(0)$ is the initial electron density, and $N_e(t)$ the electron density at time t (in years) elapsed from the recombination start. Adopting $N_e(0)\simeq 10000$ cm$^{-3}$ (mean of the density peaks in Fig. 13), and $N_e(t)\simeq 600$ cm$^{-3}$ (the lowest value in Fig. 13), we have $t\simeq 190$ years. A very sim-
ilar “recombination age” is inferred from the mean H I density of the circum-nebular matter (Sect. 3).

All this, combined with the short nebular age ($\approx 1400$ years), fairly agrees with the theoretical evolutionary times of a $0.66-0.68$ M$_\odot$ post-AGB star. According to Böckler (1995 and references therein), in the interval $t_{SW}$ (end of the superwind ejection) to $t_{SW}+1100$ yr the hydrogen-burning star crosses horizontally the H-R diagram (at $\log L_*/L_\odot \approx 4.00$) becoming hotter and hotter (up to $\log L_*/L_\odot \approx 5.20$ K). At $t_{SW}+1100$ yr the nuclear fuelling becomes insufficient, and in a century the luminosity declines to $\log L_*/L_\odot \approx 3.70$ (whereas $T_*$ reaches its maximum, $\log T_* \approx 5.30$ K). At $t_{SW}+1200$ yr the hydrogen-shell burning ceases at all, the stellar evolution drastically accelerates till $t_{SW}+1400$ yr ($\log L_*/L_\odot \approx 2.80$; $\log T_* \approx 5.20$ K), and later slows down (for example, at $t_{SW}+3000$ yr we have $\log L_*/L_\odot \approx 2.40$ and $\log T_* \approx 5.15$ K).

Summing up: NGC 6741 is close to (or has even passed) the recombination-reionization transition.

7.2. Radial ionic and mean chemical abundances, and photo-ionization model

The zvpc of the different emissions furnishes the detailed radial ionization structure of NGC 6741. Since the blurred He II appearance follows the accuracy of the F(H$\alpha$)$_{zvpc}$ distribution, we adopt $\lambda 5007$ Å as reference emission, thus inferring the radial ionization structure relative to O$^{++}$ (for details, see Benetti et al. 2003). The $\frac{\lambda_{ivity}}{N_e}$ profiles of NGC 6741 at PA$=15^\circ$ and PA$=75^\circ$ (close to the apparent minor and major axes, respectively) are presented in Fig. 14, confirming that the nebula is optically thick at all directions.

Within this scenario, the [O III] rays punching the N$_e$ peaks ($N_e$(peak)$\leq 4000$ cm$^{-3}$) according to the photo-ionization model presented in the course of the section: in these directions (barely visible in our spectral images at PA$=75^\circ$, 95° and 115°; see Figs. 4 and 10) recombination processes are less efficient, and the gas can be (partially) ionized by the UV stellar flux at larger distances.

When combined with the results stored in the previous sections, all this indicates that the overall, complex structure of NGC 6741, fully driven by the fast evolving central star, can be divided into three distinct zones showing quite different physical characteristics: the internal, high-to-medium excitation nebula directly ionized by the stellar radiation ends in a sharp transition zone at medium-to-low excitation marking the present edge of the ionization front. It is surrounded by the gas no more reached by the fading UV flux (i.e. the halo), dominated by recombination processes. A similar onion-like radial structure (ionization-transition-recombination) is observed in NGC 6565 (Turatto et al. 2002).

Though the ionization and thermal structure of NGC 6741 result to be out of equilibrium, the large $N_e$ of the ionized gas (peaks up to $12000$ cm$^{-3}$) assures a quick nebular reply to the variable stellar flux. In particular, the delay in the “transition zone” is short, the recombination time, $t_{rec}=1/(\alpha_B \times N_e)$, being a few years for hydrogen (even shorter for higher ionization species).

In conclusion: NGC 6741 is nearly in equilibrium. This allows us to neglect (in first approximation) the time dependence, and estimate the total chemical abundances of the ionized gas with the classical method valid for “static” nebulae.

We follow a two-step procedure:

I (broad approach): according to the critical analyses by Alexander & Balick (1997) and Perinotto et al. (1998), the mean ionic abundances are obtained from the line fluxes integrated over the spatial profile and the expansion velocity field; later on, we correct for the unobserved ionic stages by means of the ionization correcting factors, derived both empirically (Barker 1983, 1986), and from interpolation of theoretical nebular models (Shields et al. 1981, Aller & Czyzak 1983, Aller 1984, Osterbrock 1989). The resulting mean chemical abundances are listed in Table 3 (last but one row); the recent estimates reported in the literature are also given in the Table.

II (refining): we apply the photo-ionization code CLOUDY (Ferland et al. 1998) to a model-nebula characterized by the same distance, gas distribution, mean chemical composition and exciting star parameters of NGC 6741, and then combine the model-line profiles (convolved for a seeing+guiding of 0.60") with the line profiles observed in the true nebula.

Let us focus on the zvpc of the S-SW sector at PA$=15^\circ$ (close to the apparent minor axis of NGC 6741). The input parameters of the model-nebula are given in Table 4, whereas Fig. 15 shows the physical conditions in the model-nebula (to be compared with Fig. 13), and the absolute radial flux distribution of the main emissions in both the model-nebula and NGC 6741.

At first glance, Fig. 15 provides a satisfactory model-nebula vs. true-nebula agreement for the internal, high-to-medium excitation regions and the transition zone. Further out, the weak recombining halo appears in NGC 6741, whereas emissions are absent at all in the static model-nebula. The same is observed at the other PA.

When entering in more detail, some disturbing drifts arise in Fig. 15. Two minor discrepancies are:

(a) uncertain flux distribution of [Ne III] in NGC 6741 (ascribable to the edge location of $\lambda 3968$ Å in the original NTT+EMMI frames),

(b) comparable model-nebula vs. true-nebula flux-shift for [S II] and [S III], indicating a slight underestimation of sulphur abundance in Table 3 (last but one row), and in Table 4 (model-nebula). The same occurs for [N II]. The improved chemical abundances of NGC 6741 are reported in the last row of Table 3.

The two major problems in Fig. 15 concern:

(1) the ionization structure of helium: He I $\lambda 5876$ Å and He II $\lambda 4686$ Å are weaker and stronger, respectively, in the model-nebula than in the true-nebula;
(2) the peak emission and whole flux distribution of the highest excitation ions (He II, [Ar IV] and [Ar V]) tend to be systematically closer to the central star in the true-nebula than in the model-nebula.

Ad hoc manipulation of the model-nebula input data lowers - or even cancels - the foregoing problems; for example, we can act on the ionizing UV distribution, given the strong $T_\star$ dependence of both the ionic structure of helium and the radial profile of the highest-excitation emissions. In fact, the only decrease by 17% of the stellar temperature (i.e. for $T_\star \simeq 150000$ K, which is within the observational error box given in Sect. 6) simultaneously relieves
Table 3. NGC 6741: chemical abundances (relative to log H=12)

| Reference                  | He  | C   | N   | O   | Ne  | S   | Cl  | Ar  |
|----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Hyung & Aller 1997 (icf)   | 11.01 | 8.86 | 8.38 | 8.73 | 8.12 | 6.89 | 5.43 | 6.49 |
| Hyung & Aller 1997 (model B)| 11.04 | 8.90 | 8.15 | 8.65 | 8.00 | 6.76 | 5.34 | 6.54 |
| Pottasch et al. 2001       | 11.04 | 8.81 | 8.45 | 8.82 | 8.26 | 7.04 | -   | 6.69 |
| Pottasch et al. 2002       | 11.04 | 8.56 | 8.26 | 8.65 | 8.18 | 6.90 | 5.26 | 6.51 |
| Perinotto et al. 2004b     | 11.08 | -   | 8.31 | 8.70 | 8.16 | 6.70 | -   | 6.54 |
| This paper (icf)           | 11.04 | -   | 8.20 | 8.66 | 8.08 | 6.78 | -   | 6.54 |
| This paper (CLOUDY)        | 11.04 | -   | 8.28 | 8.66 | 8.08 | 6.90 | -   | 6.54 |

Table 4. Input parameters for the model nebula (CLOUDY)

| Radial density profile     | ionized gas = Fig. 13; cfr. Sect. 7.1 |
|----------------------------|----------------------------------------|
|                            | neutral gas = cfr. Sects. 3 and 4      |
| Chemical abundances:       | Hyung & Aller (1997) model B            |
| C, Cl, K, Ca, Mg, Si       | Table 3 (last but one row)              |
| He, N, O, Ne, S, Ar        | PN (CLOUDY default)                     |
| other elements             |                                          |
| Dust                      | PN (CLOUDY default)                     |
| Local filling factor       | 1.0                                     |
| Exciting star              | blackbody distribution                  |
|                           | $T_e=170000$ K                          |
|                           | log $L_*/L_\odot = 2.75$                |
| Distance                  | 2.0 kpc                                 |

8. The 3-D morpho-kinematical structure

According to the reconstruction method introduced by Sabbadin et al. (1985, 1987), and deepen by Sabbadin et al. (2000a, b), we select $\lambda 6686$ Å of He II, $\lambda 5007$ Å of [O III] and $\lambda 6584$ Å of [N II] as markers of the high, medium and low-ionization regions of NGC 6741, respectively. The spectral images are:

(a) de-convolved for seeing, spectral resolution and thermal motions (also fine-structure is taken into account for the recombination line of He II),

(b) de-projected through the relation $V_{\text{exp}}(\text{km s}^{-1})=13\times R''$ (see Sect. 3),

(c) assembled by means of the 3-D rendering procedure described by Ragazzoni et al. (2001).

Here we present a limited number of frames, corresponding to a partial rotation around the North–South axis centered on the exciting star (i.e. almost perpendicular to the major axis). The complete series of nebular movies is available:

- in the electronic version of the paper (on-line data),
- at [http://web.pd.astro.it/sabbadin](http://web.pd.astro.it/sabbadin), the WEB site dedicated to the 3-D structure of expanding nebulae,
- at [http://www.edpsciences.org](http://www.edpsciences.org).

Figs. 16 and 17 show the opaque reconstruction of NGC 6741 in He II, [O III] and [N II] at high and low flux-cuts, respectively, for a rotation of 180° through the first Euler angle. The (0,0) images correspond to the Earth–nebula direction (North is up and East to the left). An indication of the $N_e$ limit in Figs. 16 and 17 can be obtained from the corresponding [O III] absolute flux-cut: log $E(\lambda 5007)$ Å = -15.95 and -16.70 erg s$^{-1}$ cm$^{-3}$ (high and low cuts, respectively). Since $O/H=4.6\times10^{-4}$ (Table 3), icf(O$^{++}$)$\simeq$1.1, and $N_e \simeq 1.15\times N(H^+)$, they correspond to $N_e$(high cut)$\simeq 9000$ cm$^{-3}$ for Fig. 16, and $N_e$(low cut)$\simeq 4000$ cm$^{-3}$ for Fig. 17 (assuming $T_e=12000$ K and $\epsilon_l=1$).
Fig. 15. Model-nebula (CLOUDY) vs. true-nebula (NGC 6741, PA=15°, S-SW sector): physical conditions and radial ionization structure. Top panel: physical conditions in the model-nebula (to be compared with Fig. 13). Second panel: absolute flux distribution of H I $\lambda$6563 Å, [N II] $\lambda$6584 Å, and the ionic sequence of helium (He I $\lambda$5876 Å and He II $\lambda$4686 Å) in the model-nebula (thin symbols) and the true-nebula (thick symbols). Third panel: absolute flux distribution for the ionic sequences of oxygen ([O I] $\lambda$6300 Å, [O II] $\lambda$7320 Å, and [O III] $\lambda$5007 Å) and sulphur ([S II] $\lambda$6717+6731 Å, and [S III] $\lambda$6312 Å); same symbols as in the second panel. Bottom panel: absolute flux distribution for [Ne III] $\lambda$3968 Å, and the ionic sequence of argon ([Ar III] $\lambda$7135 Å, [Ar IV] $\lambda$4740 Å, and [Ar V] $\lambda$7005 Å); same symbols as in the second and third panels.
Fig. 16. Stereoscopic structure of NGC 6741 for a rotation around the North-South axis centered on the exciting star. Opaque reconstruction at high flux-cut for $\lambda$4686 Å of He II, $\lambda$5007 Å of [O III], and $\lambda$6584 Å of [N II], as seen from thirteen directions separated by 15°. The line of view is given by $(\theta, \psi)$, where $\theta$ is the zenith angle and $\psi$ the azimuthal angle. Each horizontal pair represents a “direct” stereoscopic pair (i.e. parallel eyes), and the whole figure provides twelve 3-D views of the nebula in as many directions, covering a straight angle (for details, see Ragazzoni et al. 2001). The (0,0) images represent the rebuilt-nebula as seen from Earth (North is up and East to the left). The complete series of nebular movies is shown in the electronic version of the paper (on-line data).
The projection of NGC 6741 for a rotation around the N–S direction (almost perpendicular to the major axis) is presented in Fig. 18 (multi-color images only in the “free” electronic version of the paper, for lack of funds), providing a representative sample of the nebular appearance when changing the line of view. The left panel, (0,0), corresponds to NGC 6741 as seen from Earth (North is up and East to the left), to be compared with Fig. 1 and the HST image by Hajian & Terzian at [http://ad.usno.navy.mil/pne/gallery.html](http://ad.usno.navy.mil/pne/gallery.html).

The overall characteristics of NGC 6741 (a hot and faint star at the centre of a dense, inhomogeneous, equatorial torus merging into a closed, ellipsoidal structure embedded into a large cocoon of almost neutral matter) closely resemble NGC 6565, a compact, recombining PN projected pole-on (Turatto et al. 2002), and show remarkable affinities with NGC 7027, the PNe prototype (Cox et al. 2002, Bains et al. 2003). Very likely, all three objects represent “middle-aged” snapshots of a massive, fast evolving post-AGB star.

### 9. Discussion

In spite of the nebula compactness, we have quite success fully applied the tomographic and 3-D analyses to NGC 6741, covered at high spatial and spectral resolutions with ESO NTT+EMMI.

NGC 6741 is a young (age≈ 1400 years) PN at a distance of 2000 pc; a case of a high-excitation, almost-prolate ellipsoid (0.039 pc x 0.022 pc x 0.019 pc; major, intermediate and minor semi-axes, respectively) denser at the equator than at the poles (Ne peaks up to 12000 and 7000 cm$^{-3}$, respectively), surrounded by a thin skin at low-excitation (the transition zone, corresponding to the present ionization front), and embedded into an extended, spherical (radius=0.080 pc), almost neutral recombining halo containing a large fraction of the nebular mass (M$_{halo}$ ≥0.20 M$_\odot$ versus M$_{ion}$ ≃0.06 M$_\odot$).

The complex ionization structure of NGC 6741 is fully driven by the fast evolution of the central star, a massive (0.66-0.68 M$_\odot$), hot (log T$_e$ ≥5.23 K) and faint (log L$_e$/L$_\odot$ ≃2.75) post-AGB star fading towards the white-dwarf region (after exhaustion of the hydrogen–shell nuclear burning).

The ionized gas of NGC 6741 follows the general expansion law $V_{exp}$ (km s$^{-1}$)=13×$R_e^{0.20}$, except the innermost, highest-excitation layers, showing clear evidences of deceleration. This peculiar kinematical behaviour can be qualitatively ascribed to the luminosity drop of the central star (Schönberner et al. 1997, Steffen et al. 1998, Marigo et al. 2001, Perinotto et al. 2004a); in this evolutionary phase the stellar mass-loss quickly decreases, and the falling hot-bubble’s pressure no more balances the pressure of the ionized gas, so that the contact discontinuity and the adjacent, high-excitation nebular layers accelerate inwards.

The argument is known, and deserves more attention, the kinematical properties of the innermost layers being an excellent diagnostic of the star-nebula interaction. A search for more “decelerated” candidates, a high-resolution spectroscopic survey in ionic species at large IP, and the detailed comparison with the current hydrodynamical simulations are highly desired.

Note that the opposite situation (i. e. acceleration) is expected for the external, recombining layers of NGC 6741, whose de-pressuring gives rise to Rayleigh-Taylor instability at the ionization edge. Though the knotty and filamentary [N II] nebular appearance (Fig. 1, lower panel) qualitatively agrees with this scenario, its confirmation needs very-high spectral resolution (R≥100,000) echellegrams detecting the increase of expansion velocity (and turbulence!) at the ionization edge.

A further interesting point concerns the wide radial matter distribution of NGC 6741 (much wider than the $N_e$ profile given in Fig. 13, due to the presence of the dense, almost-neutral recombining halo). This indicates a modest contribution of wind interaction to the nebular shaping (it essentially supports the innermost layers, avoiding gas infall), whereas the lion’s share is taken by ionization: the thermal pressure of the ionized gas accelerates the matter outwards and decelerates inwards, creating the density and velocity distributions observed in NGC 6741 (more general comments are towards the end of the section).

Though the precise radial profile of the matter remains unknown - a large fraction of NGC 6741 being neutral -, a more sign provides that the outer radius of the main nebula extends well beyond the present ionization edge: the absence of any extended, diffuse, faint and roundish AGB-halo emission in the Palomar Sky Survey plates, deep imaging by Schwarz et al. (1992), and HST frames. This is confirmed by our spectra: no kinematical signature of an AGB-halo (i. e. external, faint, un-tilted and un-split emission) appears. Since the low-density gas of an AGB-halo (usually $N_e$=50 to 200 cm$^{-3}$; Chu et al. 1987; Corradi et al. 2003) is little affected by recombination (from Eq. (14), $N_e(0)$=50 to 200 cm$^{-3}$ implies $N_e(200yr)$=47 to 162 cm$^{-3}$), we infer that:

- NGC 6741 never became optically thin to the UV stellar radiation,
- the total nebular mass, M$_{tot}$, is larger than 0.40 M$_\odot$.

Let us focus on recombination, which appears as the main characteristic (and peculiarity) of our nebula. As outlined in the previous sections, NGC 6741 is the second PN - of the six so far analysed with the 3-D methodology - in a deep recombination phase (the first being NGC 6565, Turatto et al. 2002). Moreover, according to Benetti et al. (2003), a third nebula, NGC 6818, is at the very beginning of recombination. Such an apparent excess of recombining PNe is a mere consequence of our target selection criteria (in particular, high surface brightness and richness of ionic species), favouring massive nebulae powered by fast evolving central stars.

Thanks to the unprecedented accuracy achieved by tomography and 3-D recovery on the manifold facets of the PN research, we have identified a number of observational evidences supporting the recombination hypothesis...
for NGC 6741; they are:
(1) nebula much brighter than the star (Sects. 1 and 6),
(2) presence of absorbing knots (Sect. 1),
(3) co-existence of ionic species in a large IP range (Sects. 1, 3 and 7.2),
(4) kinematics of the halo (Sect. 3),
(5) high density of the almost-neutral halo (Sects. 3 and 4),
(6) \(c(\text{H} \beta)\) variable over the nebula (Sect. 4),
(7) high temperature and low luminosity of the central star (Sect. 6),
(8) \(T_{\text{g}2} \text{H I} > T_{\text{g}2} \text{He II}\) (Sect. 6).

A minimal, but effective, recombination standard for the whole PN class - in practice, a summary of points (1) and (7) - is given by:

\[
m(V_\ast)_\text{obs} + \log F(\text{H} \beta)_\text{obs} - 1.1 \times c(\text{H} \beta) > 5.0, \quad (15)
\]

where \(F(\text{H} \beta)_\text{obs}\) is in erg cm\(^{-2}\) s\(^{-1}\).

A quick look at the Strasbourg–ESO Catalogue of Galactic PNe (Acker et al. 1992) allowed us to select some fifty targets satisfying Eq. (15). Half of them (e. g. NGC 2440, Hb 4, NGC 6565, NGC 6537, NGC 6620, NGC 6741, NGC 6886, NGC 6881, NGC 7027, Hn 1-2, NGC 6302, and NGC 6563) are compact (sometimes with butterfly-like extentions), at high surface brightness, and represent young recombining PNe ejected and excited by a massive \((M_\ast \geq 0.64 \, M_\odot)\) fast evolving star beyong the turn-around point in the H–R diagram. The remaining candidates are mean-to-low surface brightness, extended (often bipolar) nebulae (e. g. NGC 6445, NGC 6439, A 55, NGC 6772, A 53, NGC 6818, NGC 6894, NGC 7048, NGC 2438, NGC 2818, and IC 4406), corresponding to aged, evolved PNe, optically thick (at least in some directions) to the fading UV radiation of a moderately-massive \((0.60 \leq M_\ast \leq 0.64 \, M_\odot)\) post-AGB star in the white dwarf cooling sequence.

Further supports to the “massive” nature for the central stars of PNe satisfying Eq. (15) are:
- most targets belong to the morphological class B of Greig (1971, 1972),
- a large fraction consists of Type-I PNe (Peimbert 1978; Peimbert & Torres–Peimbert 1983; Torres–Peimbert & Peimbert, 1983; Peimbert et al. 1995),
- the \(\text{H}_2\) emission at 2.12 \(\mu\)m is commonly detected (Kastner et al. 1996; Natta & Hollenbach 1998; Bohigas 2001). Note that, though NGC 6741 is not listed among the \(\text{H}_2\)-emitters, a deep search promises fruitful results.

The general rule for recombining PNe is that, the higher the surface brightness of the nebula, the larger is the mass of the star.

Summing up: recombination represents a not uncommon evolutionary phase in PNe; it becomes unescapable for massive nebulae ejected and excited by a massive, fast-evolving post-AGB star (also see Tyldenda 1986, Szczzerba 1990, Phillips 2000, Marigo et al. 2001, Turatto et al. 2002, Benetti et al. 2003, and Perinotto et al. 2004a).

Let us close this verbose paper with some general considerations on the kinematics of the whole PN class. The comparative analysis performed in Sect. 3 - rejecting the kinematical results based on spherical symmetry assumption and/or emission profiles of recombination lines integrated along the slit - enhances the rarity of real nebulae showing a “U”-shaped expansion velocity field.

We stress that:

(a) Wilson’s law \((V_{\text{exp}} \propto R)\) is the general rule for PNe (Wilson 1950, Weedman 1968, Sabbadin et al. 2004 and references therein);

(b) at present, only BD+30°3639 and NGC 40 show clear observational evidences of a soft acceleration in the innermost layers (Bryce & Mellema 1999; Sabbadin et al. 2000a). Both objects: (I) are very-low excitation PNe (I([\text{O III}] λ5007 A) < I(\text{H} \beta)), (II) exhibit an extremely sharp radial matter profile (shell thickness \(\Delta R/R < 0.25\)), and (III) are powered by a “cold” and bright central star of late-WR spectral type. According to Iben et al. (1983), Blöcker (1995, 2001), and Herwig et al. (1999), they represent “born-again” PNe (i. e. the hydrogen-deficient star suffers a late thermal pulse during the motion towards the white-dwarf region. Due to the pulse-induced convection, hydrogen mixes and burns on a convective turn-over time scale);

(c) three more “born-again” candidates - A 30, A 58 and A 78 - are faint, extended PNe presenting a central, complex structure of fast, hydrogen-deficient knots (Jacoby 1979, Pollacco et al. 1992).

All this calls for severe constraints to the evolutionary parameters responsible of PN shape and shaping (in particular, wind interaction). In fact, according to the detailed radiation-hydrodynamics simulations (Perinotto et al. 2004a, and references therein), a PN is the result of the synergistic effects of ionization and fast wind on the gas ejected during the superwind phase, generating a typical double-shell structure (inner “rim” + outer “shell”) characterized by a “U” or better “V”-shaped expansion velocity field. The double-shell structure may only be destroyed either by recombination of the “shell” when the central star fades, or by overtaking of the “shell” by the “rim”. In both cases a single-shell configuration emerges, whose expansion velocity field is simple and increases always steadily inwards.

Wind interaction being the main responsible of the “V”-shaped expansion profile in double-shell model-PNe, as well of the increasing inwards velocity field in single-shell model-PNe, we infer that all current radiation-hydrodynamics simulations tend to overestimate the dynamical effects of fast stellar wind on the nebular gas (we suspect that post-AGB mass-loss rates adopted by the theoretical simulations are systematically too high). Though the same suspect arose in the study of NGC 6565 (Turatto et al. 2002), NGC 6818 (Benetti et al. 2003) and NGC 7009 (Sabbadin et al. 2004), a quantitative answer (also including: (a) the temporal evolution of mass-loss in the superwind phase, Schönberger et al.
2005, and (b) the binarity and the possible role of magnetic fields, Garcia-Segura & Lopez 2000; Blackman et al. 2001) will come from the detailed analysis performed on a representative sample of PNe in both hemispheres, covered with ESO NTT+EMMI and TNG+SARG (work in preparation).

10. Conclusions

In our opinion, PN observers should cancel the word “average” (and respective synonyms) from their scientific vocabulary: no more average line fluxes, integrated spectral profiles, mean electron temperature, overall electron density, and so on. In fact, to bridge the historical gap between theory and practice (Aller 1994), we need detailed, point-to-point flux and velocity measurements in a wide ionization range, combined with a straightforward, versatile methodology of analysis. To this end, we have applied tomography and 3-D recovery (Sabbadin et al. 2004 and references therein) to long-slit echellograms of the compact, bright PN NGC 6741, covered at nine PA with ESO NTT+EMMI.

Our long-lasting journey started with the gas kinematics, penetrated into the galactic and circum-nebular absorptions, and explored the nebular distance, mass and age. Later on, we dealt with the stellar properties, pushed through the nebular physical conditions, ionization structure and photo-ionization model, went over the stumbling block of image de-projection, and, at last, flew about the multi-color and opaque reconstructions of the nebula.

The wealth and accuracy of the results here presented:

- confirm the unique capacity of tomography and 3-D recovery in extracting the huge amount of physical information stored in high-resolution spectroscopy (a tacit invitation, extended to the worldwide researchers),
- stress once more that properly squeezed echellograms do represent a peerless tool for deeping the kinematics, physical conditions, ionization structure and evolution of all classes of expanding nebulae (PNe, nova and supernova remnants, shells around Population I Wolf-Rayet stars, nebulae ejected by symbiotic stars, bubbles surrounding early spectral-type Main Sequence stars etc.).

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Fig. 17. Same as Fig. 16, but at low flux-cut.
Fig. 18. Optical appearance of NGC 6741 (multi-color in the electronic version of the paper; blue=He II, green=[O III], red=[N II]) for a rotation through the N–S axis centered on the exciting star. The left panel, (0,0), corresponds to the re-built nebula as seen from the Earth (North is up and East to the left). Recall that \( \text{projection}(\theta, \psi) = \text{projection}(\theta \pm 180^\circ, \psi \pm 180^\circ) \). The complete (multi-color) movie is shown in the electronic version (on-line data).