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The kinematics of an ionized shell, NGC 7635, in the S162 complex*

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Abstract. The complicated kinematic structure of the ($\simeq$ 3 pc) diameter shell nebula NGC 7635 (itself part of a system of shells in the broader S162 area) has been revealed by observations of spatially resolved Hα and [NII] line profiles. The observations were obtained with the Manchester echelle spectrometer on the William Herschel and Isaac Newton telescopes along NS lines of measurement distributed over the filamentary nebula. We propose a model where the stellar wind from the exciting star pressurises an ionized layer which is itself in pressure equilibrium with the molecular cloud. Irregular expanding shells are also produced by the breakout of the stellar wind from the surface of the cloud.

Key words: ISM: S162 – ISM: NGC 7635 – ISM: bubbles – ISM: kinematics and dynamics – stars: mass loss

1. Introduction

The $\approx$ 3′ diameter filamentary nebula NGC 7635 (also known as the Bubble nebula) is the most prominent feature in a complex of interlocking shells belonging to the emission nebula S162 (Sharpless 1959). This complex extends over a much broader area of 30′ × 35′ and is situated in the Perseus arm (Georgelin et al. 1973) at a distance of $\simeq$ 3.5 kpc (Georgelin 1975). The complicated morphology of the area is clearly discernible on a broad-band photograph taken in red light (see Barlow et al. 1974).

NGC 7635 comprises the ‘inner’ shell of the complex as shown in the sketch in Fig. 1a. and is surrounded by a second fainter and more diffuse shell $\simeq$ 7′NS × 9′EW in extent; the northern edge of this ‘intermediate’ shell coincides with the ‘inner’ shell. A third more extensive and irregular faint ‘outer’ envelope is also discernible as are a number of condensations lying within diffuse matter to the north.

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* Based on observations made with the William Herschel and Isaac Newton telescopes, La Palma.

The radio structure of the NGC 7635/S162 based on data taken with an angular resolution of 24″ × 28″ shows strong similarities with the complicated optical morphology; NGC 7635 itself has an optically thin thermal radio spectrum (Israel et al. 1973).

The ionized mass of the shell nebula NGC 7635 is in the range of 3.5–4.5 $M_\odot$ (Israel 1977; Doroshenko 1972). The root-mean-square electron density is in the range of 300–500 cm^{-3} (Doroshenko 1972; Israel 1977; Sabbadin & Bianchini 1977) although peak values associated with highly condensed knots on the northern part of the shell are in the range of 5000–10000 cm^{-3} (Deharveng-Baudel 1973; Sabbadin & Bianchini 1977; Lynds & O'Neil 1983; Chavarria et al. 1987). The electron temperature reported by various authors is in the range of 7500–15000 K, depending on the position measured and the method employed (see, e.g., Doroshenko 1972; Kazès et al.1977; Sabbadin & Bianchini 1977). The visual extinction over NGC 7635 is $\simeq$ 2 mag apart from the northern part where it is higher, $\simeq$ 3–4 mag (Barlow et al. 1976; Lynds & O'Neil 1983; Chavarria et al. 1987).

The ionisation of NGC 7635 and the more extended S162 region is generally attributed to the massive and extremely luminous Of star BD+60°2522 (V = 8.7) which is located 62″NE of the geometrical centre of NGC 7635 This star (henceforth called the ‘central star’) belongs to the Cassiopeia OB2 association consisting mainly of early B-type giants and supergiants (Humphreys 1978) and its distance is estimated at 3.6 kpc (Israel et al. 1973; Johnson 1982). The physical parameters of the central star and its energetic stellar wind (Leitherer 1988) compiled from the work of various authors are presented in Table 1.

NGC 7635 lies on the edge of a low density diffuse molecular cloud, a conclusion derived from the mapping of the CO emission over a 8′ × 15′ area surrounding the SW part of the Bubble nebula (Thronson et al. 1982). Additionally, infrared studies of the broader area provide evidence of thermal re-emission of the stellar UV radiation absorbed by the dust contained within the ionized gas and the associated neutral - molecular complex (Thronson et al. 1982). The asymmetric position of BD+60°2522 suggests a close association of this star and the diffuse molecular cloud.

Table 1. Parameters of the ionising star of NGC 7635

Parameter		Remarks	References
1. Ionising star			
BD number	60°2522		
l	112°.3		
b	0°.2		
Spectral type	O5		Doroshenko 1972
	O6		Viotti & Nesci 1974
	O6.5 IIIef		Conti & Leep 1974
M_{bol} (mag)	−9.7		Morton 1969
M_v (mag)	−6.3		Conti & Alschuler 1971
V (mag)	8.7		Lynds & O'Neil 1983
$E(B-V)$ (mag)	0.73		Morton 1969
	0.65		Lynds & O'Neil 1983
A_v	2.26		Israel et al.1973
	2		Doroshenko 1972
D(kpc)	3.6		Georgelin 1975
			Johnson 1982
Heliocentric radial velocity	−26		Wilson 1953
V_{HEL} (km s^{-1})	−29	(1)	Viotti & Nesci 1974
Rotational velocity (km s^{-1})	240	(2)	Viotti & Nesci 1974
2. Stellar wind			
Terminal wind velocity	1800		Johnson 1980
V_W (km s^{-1})	2700		Johnson 1982
	2200		Johnson 1982
	2500		Leitherer 1988
Rate of stellar mass loss ($M_\odot$yr^{-1})	$10^{-5.76}$		Leitherer 1988

Remarks to Table 1

1. The strong CaII radial velocity is -29 km s^{-1} but the stellar radial velocity is very uncertain due to the large width of the lines.
2. The line broadening corresponds to a rotational velocity $V_R sin\ i$ = 240 km s^{-1}.

The available kinematic information concerning NGC 7635/S162 is given in Table 2. The bulk of the ionized gas has a mean heliocentric radial velocity of −55 kms^{-1} which is similar to that of the molecular cloud (see Table 2). The absence of any significant discontinuity in radial velocity between NGC 7635 and the extended S162 confirms that both belong to the same complex (Maucherat & Vuillemin 1973). Expansion velocities of 4-25 kms^{-1} have been reported for NGC 7635 under the assumption that it is a simple, radially expanding, spherical shell (Deharveng-Baudel 1973; Maucherat & Vuillemin 1973; Pismis et al. 1983).

The previous observations concentrate on measurements of the global expansion velocity of the nebula. Consequently, spatially resolved observations of line profiles have now been made over NGC 7635 to investigate its detailed kinematic behaviour: the complex morphology suggests that a more complicated model than a simple radially expanding spherical shell may be appropriate.

2. Observations and results

Long-slit observations of NGC 7635 were taken with the Manchester echelle spectrometer (Meaburn et al. 1984) in its primary mode combined with the 4.2-m William Herschel Telescope (WHT) and the 2.5-m Isaac Newton Telescope (INT). The observations were taken at the converted $f/7.9$ focus of the WHT and the $f/15$ Cassegrain focus of the INT. A 90 Å bandwidth interference filter was employed to isolate the 87th echelle order containing the Hα and the [NII] emission lines. The Image Photon Counting System or IPCS (Boksenberg & Burgess 1973) was the detector. The single entrance slit was oriented NS and located at the Positions 1–6 shown in Fig. 1. The parameters of the observations are summarised in Table 3.

The IPCS detector format for Position 1 was 1260 channels along the dispersion direction and 260 increments (numbered 1–260 from S to N) each corresponding to 0.″750 over the 3.′25 length of the slit. The format for Positions 2–6 was 1020 channels along the dispersion direction and 240 increments (numbered 1–240 from S to N) each corresponding to 0.″534 over the 2.′14 length of the slit. Cu–Ar arc spectra were used to calibrate the data spectrally to ±1 km s^{-1} accuracy. All the data were

Table 2. Mean heliocentric radial velocities of several components of the NGC 7635/S162 complex

Spectral line(s)	V_{HEL} (⋆) km s^{-1}	Remarks	References
Various lines	−55.3		Courtès et al. 1968
Hα	−52.6		Georgelin & Georgelin 1970
Hα	−56.3		Deharveng-Baudel 1973
Hα	−55.0	(1)	Maucherat & Vuillemin 1973
Hα	−55.7		Georgelin 1975
Hα	−54.3	(2)	Reynolds 1983
[NII]	−51(±3.5)	(3)	Pismis et al. 1983
Hα,Hβ,HeI,[NII] [OIII],[OII],[SII]	−55(±13)	(4)	Lynds & O'Neil 1983
Hα,Hβ,[OIII],[NII]	−49(±7)	(5),(6)	Chavarria et al.1987
H109α	−54.4		Kazès et al. 1977
H137β	−51.5		Kazès et al. 1977
HI (21 cm absorption)	−62.3		Kazès et al. 1977
CO	−55.0		Blitz et al. 1982
CO	−55.5		Thronson et al. 1982

* $V_{HEL} = (V_{LSR} - 10.3)$ km s^{-1}

Remarks to Table 2

1. Mean V_{HEL} estimated for several positions over NGC 7635/S162 and measured from two interferograms. Although in the original paper the velocities in the captions 1 and 2 are referred to as V_{LSR} this is probably due to an error as already pointed out by Pismis et al. (1983).
2. For the position $l = 112°$, $b = 0°$.
3. Average of 267 velocity measurements over S162.
4. Mean V_{HEL} estimated from the measurements along 22 spectra.
5. Mean V_{HEL} estimated from Coudé long-slit spectrograms of NGC 7635. No velocity variations from line to line eastward of the star were detected. A significant radial velocity difference of (+12 ± 1)km s^{-1} was detected at the knots.
6. Over the shell the line width (HPBW) of Hα is ≃ 30km s^{-1}.

Table 3. Parameters of the observations

Position	Telescope	Position of slit	Slit width	Slit length (arcmin)	Integration time (s)
1	WHT	NS	$150\mu \equiv 0.''93 \equiv 11$km s^{-1}	3.25	4537
2	INT	NS	$70\mu \equiv 0.''40 \equiv 8$km s^{-1}	2.14	1867
3-6	INT	NS	$70\mu \equiv 0.''40 \equiv 8$km s^{-1}	2.14	1200

reduced using STARLINK software (in particular the Longslit software of Wilkins and Axon). Greyscale representations of the position-velocity (P–V) data array containing the [NII] profiles along the slit Position 1 are shown in Figs. 2a–b. The faint, high-speed features are more apparent in the high-contrast image of the [NII] array in Fig. 2a than in the equivalent Hα one because of the somewhat higher [NII] surface brightnesses and the smaller thermal widths of the [NII] profiles.

Increments along the slit length for Position 1 were binned together in blocks of five and for Positions 2–6 mostly in blocks of six in order to increase the signal to noise ratio. The lower increments for Positions 2–5 were binned together in greater blocks because of the faintness of the signal. The resultant profile from each co-added cross-section was fitted, conservatively, with one or two Gaussians as appropriate. Typical co-added profiles from this process are shown in Fig.3a–c. These are from the incremental lengths marked a, b and c in Fig. 2a. along the slit length of Position 1.

The heliocentric radial velocities, V_{HEL}, of the separate velocity components in the Hα profiles that were derived by this process along the six slit lengths are shown in Fig. 4. In each profile the encircled dots indicate dominant components, the dots weaker components and the crosses very faint components. The corresponding [NII] results,which are not presented here, show a striking similarity with those presented in Fig. 4.

3. Discussion

The radial velocities of $V_{HEL} \approx -55$ km s^{-1} of the bright, single profiles at the edge of NGC 7635 (see Fig. 4) coincide closely with the average radial velocity of the adjacent CO molecular

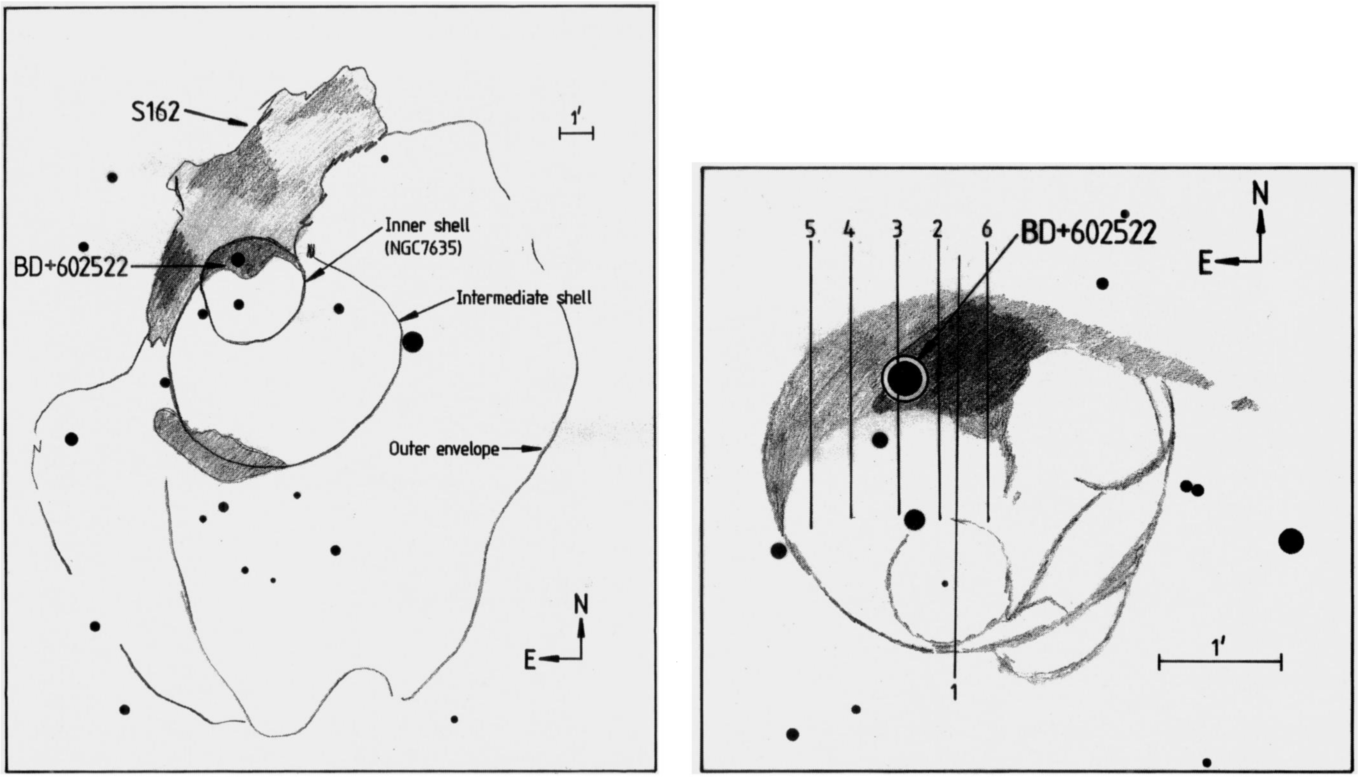

Fig. 1. a A sketch of the interlocking shells of the NGC 7635/S162 complex. **b** Positions of the slit (1–6) against a sketch of NGC 7635

cloud. A close association of the HII region and the molecular cloud is implied in agreement with Thronson et al. (1982). Such HII shells around regions of recent star formation are commonly found on the dense, molecular edges of large clouds of neutral interstellar matter.

The complicated internal motions of NGC 7635 that are found here (see Figs. 2 a–b and 4) should be expected in view of the complex morphology of this shell-like nebula (see Fig. 1). The reasonable assumption that it has been created in an ambient medium with a strong density gradient away from the molecular cloud can explain such complexity.

Firstly, the approximate equality of velocities of the molecular cloud and the bright nebulosity places constraints on the models of the interaction of BD+602522 with its surroundings. In particular, if the two regions are adjacent, they must be in rough pressure equilibrium to avoid significant velocity differentials between them. The ionized gas pressure must also be roughly equal to the ram pressure it experiences from the strong stellar wind (see Table 1) of BD+602522.

The pressure in the ionized gas is extremely uncertain since the large differences between the rms electron density ($< n_e^2 >^{1/2} \approx$ 300–500 cm^{-3}) and the peak local density ($n_e \approx 5 \times 10^3$–$10^4$ cm^{-3}) imply considerable clumping. It is likely that this clumpy structure reflects the clumpy structure of the molecular cloud (Thronson et al. 1982). The filling factor of the ionized gas is in the range $\epsilon \approx 10^{-3}$–10^{-4} from the above density differences, and therefore the mean density $< n_e > \approx$ 5–100 cm^{-3}. The associated pressure is $< P_e > \approx (7–140)\times 10^{-12}$ dyne cm^{-2} for an electron temperature of 10^4K. For pressure equilibrium between the ionized gas and molecular cloud material, the mean density in the molecular cloud must be $< n_c > \approx 10^3 - 2\times 10^4$ cm^{-3} for an assumed molecular cloud temperature $T_c \approx 50$ K. If the filling factor in the molecular cloud were similar to that in the ionized gas, clump densities $n_c \approx 10^5 - 2\times 10^7$ cm^{-3} for an assumed molecular cloud temperature $T_c \approx 50$ K are implied, reasonably consistent with those suggested by the environs of ultra-compact HII regions where stars of similar mass to BD+602522 are present (Churchwell 1990).

If the 'central' star is situated at a distance d from the ionized region, the wind pressure is $P_w \approx \dot{E}_*/(2\pi d^2 V_*)$ where $\dot{E}_*$ ($\approx$ (1.7–14) $\times 10^{36}$ erg s^{-1}) is the wind mechanical luminosity and V_* (1800–2700 km s^{-1}) is the wind velocity (Table 1). Hence $P_w \simeq (1.6–2.5)\ 10^{-10}\ (d/\mathrm{pc})^{-2}$ dyne cm^{-2} and with the range of $< P_e >$ above, $d \simeq (1-6)$pc, i.e. comparable to the observed shell radius. The ionized layer must have a thickness ℓ_i sufficient to absorb the Lyman continuum photons from the star, i.e. $\ell_i \approx S_*/(4\pi d^2 < n_e^2 > \beta)$, where S_* is the stellar output rate in the Lyman continuum and β is the hydrogen recombination coefficient. We adopt $S_* \approx 5\ 10^{49}$ s^{-1} for a star of spectral type O6.5III (Panagia 1973) and thus $\ell_i \approx$ 0.07–7 pc. On general grounds we would not expect ℓ_i to exceed the present bubble radius (the inner shell in Fig 1a, $\approx$ 1.5pc) and the upper limit in ℓ_i is almost certainly far too high.

The mean total hydrogen column density through the molecular cloud is $\lesssim 5\ 10^{21}$ cm^{-2} (Thronson et al. 1982) and using

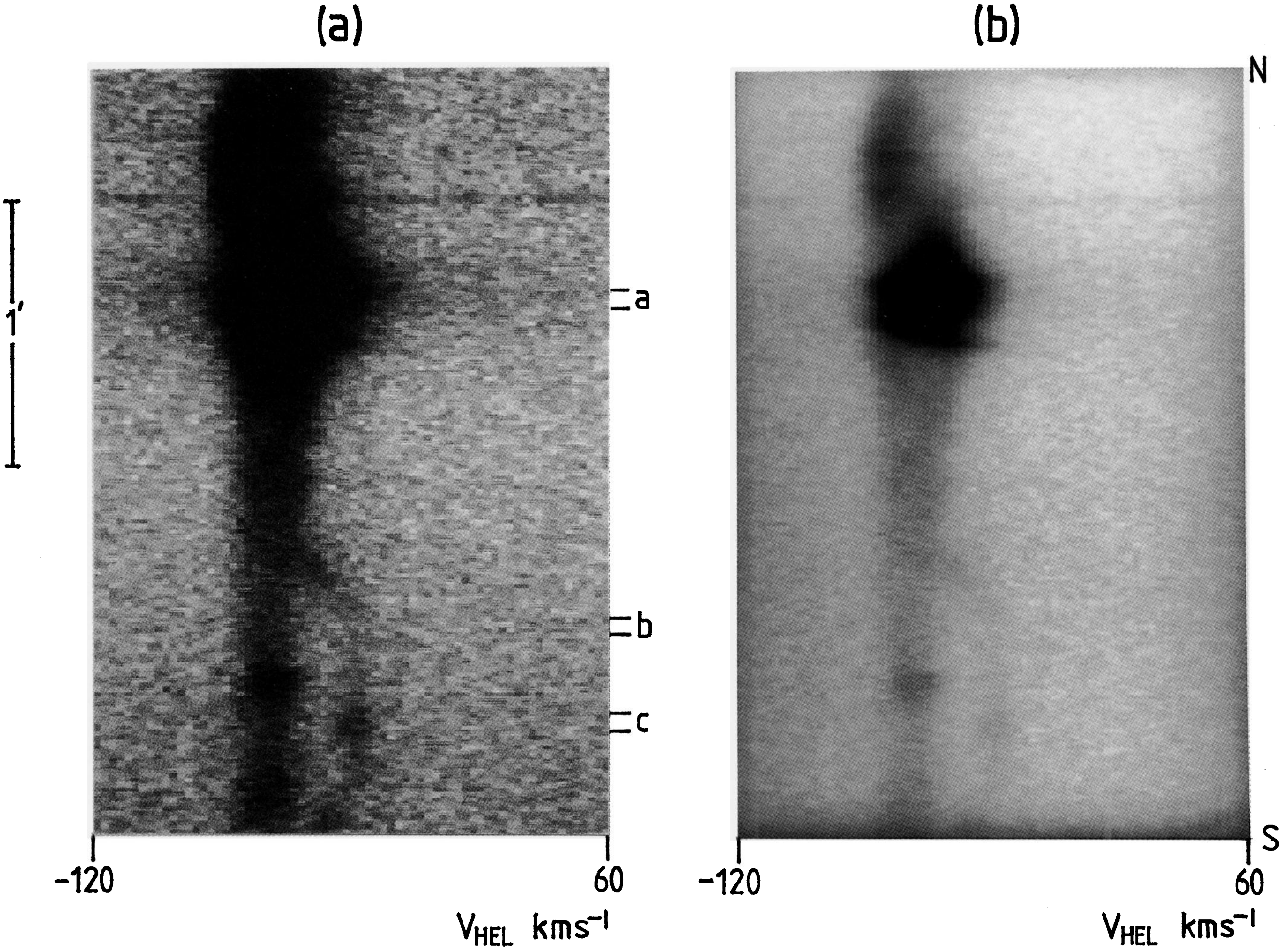

Fig. 2. Negative greyscale representations at high and normal contrast (a & b respectively) of the position versus velocity data for the [NII] line profiles along slit Position 1. The incremental lengths marked a, b & c in Fig. 2a are where the profiles shown in Fig. 3a–c were obtained

the range of $< n_c >$ derived above, it has a linear size along the sight-line of $\ell_c \lesssim$ (0.08–1.6)pc. Hence, at most, the molecular cloud thickness is comparable with that of the ionized layer and it seems likely that the cloud has been largely destroyed by its interaction with BD+602522.

The velocity of the ionized molecular interface must be $\lesssim c_s$, the sound speed in the molecular material. The destruction time of the cloud using the range of ℓ_c given above is $t_d \ell_c / c_s \approx$ (0.8 – 16) 10^5 $(100\mathrm{K}/T_c)^{1/2}$ yr, where T_c is the temperature of the molecular gas. Thronson et al. (1982) note the serious problem of the short CO photodissociation timescale ($\approx$ 20 yr) if the molecular cloud is homogeneous. They suggest as one possibility for circumventing this that the molecular cloud is clumpy. This is completely consistent with our model discussed above.

The velocity components at up to +35 km s^{-1} ($V_{HEL} \approx -20$ km s^{-1}) with respect to the molecular cloud (see Figs. 2a–b and 4) are presumably produced in an irregular shell (see Fig. 2a) driven on the far side of the cloud by the action of the wind down the density gradient, i.e. outwards from the molecular cloud. The ambient density ρ_0 which gives a shell velocity V_s under the action of a wind driving pressure P_w is just $\rho_0 \simeq P_w/V_s^2$; if we assume that this shell is also a distance $r_s \approx 1.5$ pc from the star and $V_s \approx 35$ km s^{-1}, then approximately $\rho_0/m_{\mathrm{H}} \approx 10$ cm^{-3}, appreciably less than the lower limit for the mean cloud density $< n_c >$ given above and consistent with the interpretation as a shell breaking out of the edge of the molecular cloud. Very approximately, the lifetime of the high velocity shell is $r_s/V_s \approx 5\ 10^4$ years and suggests that this is a young and relatively short lived phenomenon. A sketch of the proposed model is shown in Fig. 5.

An explanation of the further shell-like structure that appears to enclose NGC 7635 ('intermediate shell' see Fig. 1a) must await measurements of radial velocities across its diameter. It may be unrelated to NGC 7635 and simply along the same sightline though there are no obvious candidates as driving sources. Alternatively, it may be a consequence of earlier episodic activity of BD+602522 but this is difficult to envisage. Possibly it is an approaching 'blow-out' driven by the same wind which is forming NGC 7635.

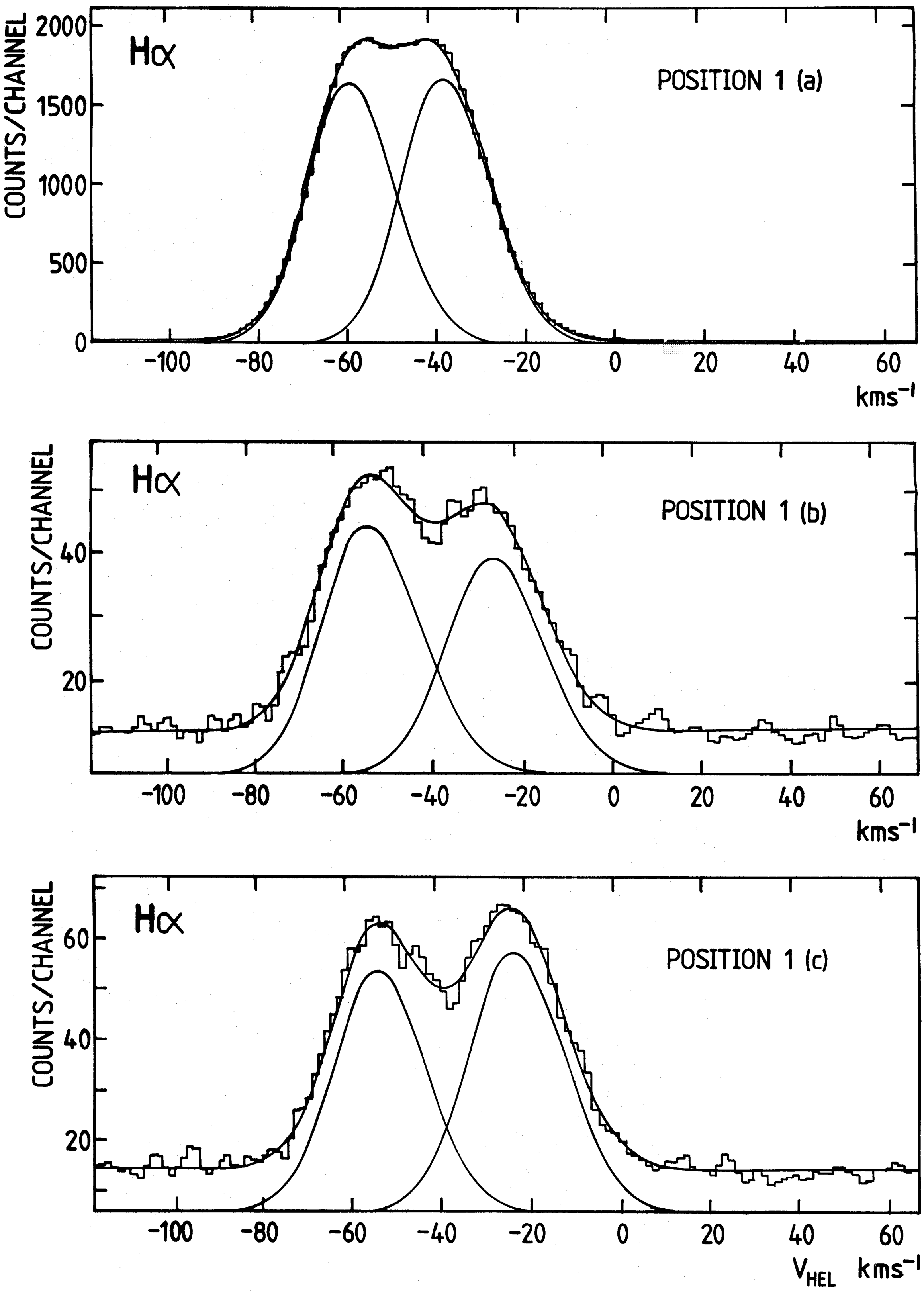

Fig. 3. Best fit of two Gaussians to the Hα line profiles for the incremental lengths a, b and c identified in Fig. 2a

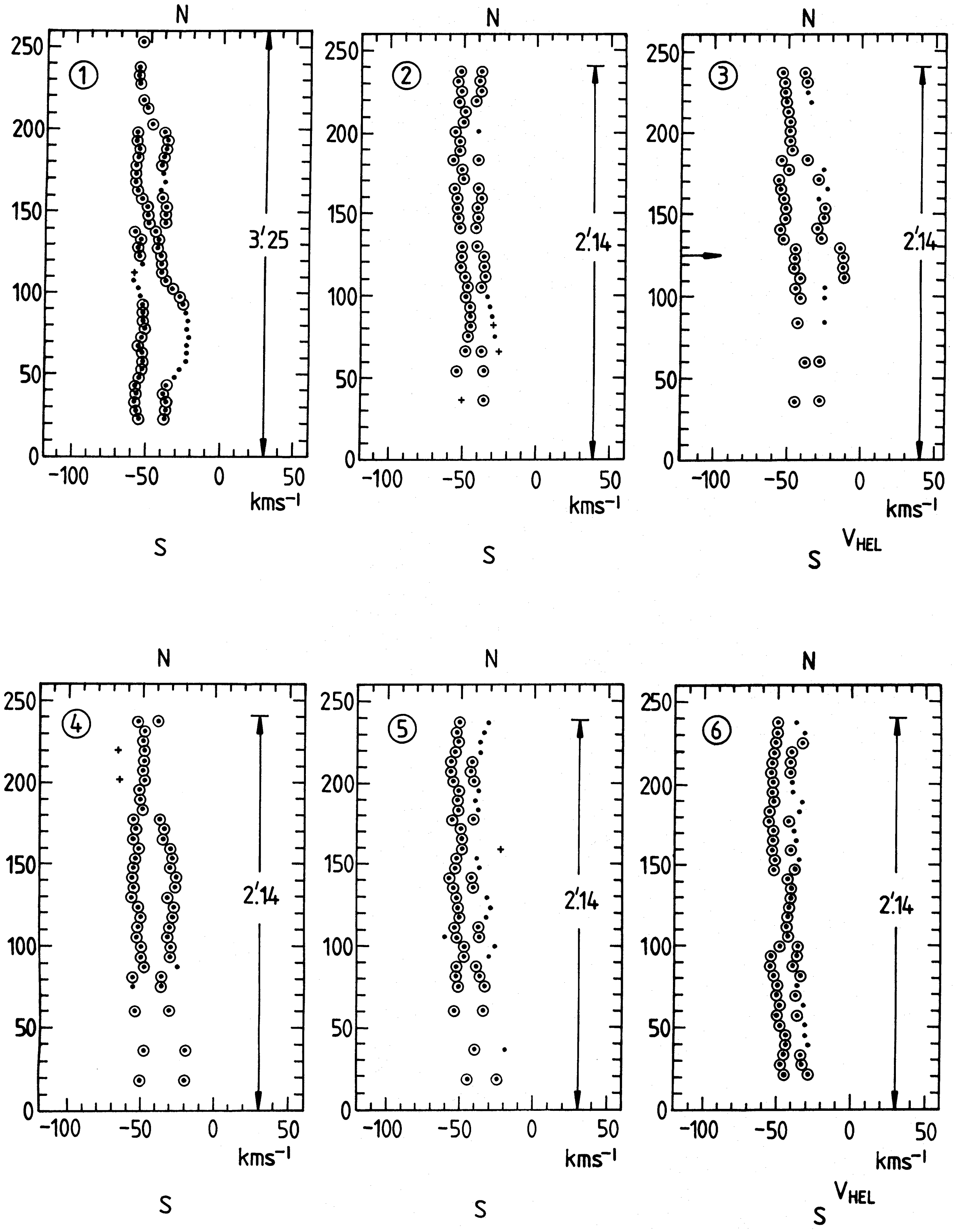

Fig. 4. The separate velocity components in the Hα line profiles along slit lengths for Positions 1–6. Encircled dots indicate dominant components, dots weaker components (≤ 70% of the brightness of the dominant component) and crosses fainter components (≤ 30% of the dominant). The arrow in 3 indicates the star BD+602522

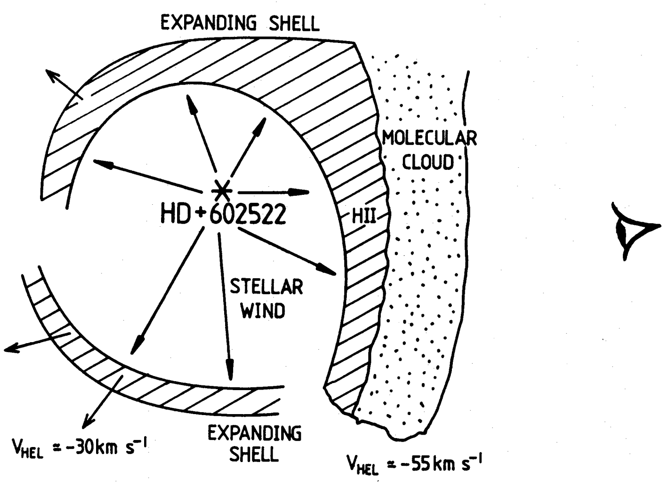

Fig. 5. A sketch of the schematic model in which the stellar wind from BD+602522 creates NGC 7635

We finally note that our Fig 5 places the HII region on the far side of the molecular cloud with respect to the observer. This is completely consistent with the optical extinction estimated by Thronson et al. (1982).

4. Conclusions

We have proposed a model for NGC 7635 in which a stellar wind from the exciting star pressurizes an HII layer which itself is in pressure equilibrium with a very clumpy molecular cloud. This explains the coincidence of the ionized and molecular gas radial velocities. The destruction time of the molecular cloud is long because the ionized–molecular interface moves very slowly with respect to the molecular material. The molecules in the neutral cloud can exist over long timescales near such a powerful exciting star precisely because the cloud material is very clumpy. High velocity components in the ionized gas are produced by the action of the stellar wind on lower density parts of the molecular cloud.

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