

Interactions of stars and interstellar matter in Scorpio Centaurus

E. J. de Geus^{1,2}

¹ Sterrewacht Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands

² Department of Astronomy, University of Maryland, College Park, MD 20742, USA

Received November 22, 1990; accepted February 13, 1992

Abstract. In this paper the interaction of the stars in the Scorpio-Centaurus OB association with the ambient interstellar medium is investigated. Large H I loops in the fourth galactic quadrant are parts of expanding shells surrounding the subgroups of the association. The energy output of the original stellar population of the subgroups is calculated. Comparison with the kinetic energy of the shells shows that the energy output of the stars in the subgroups is sufficient to form the shells. The masses of the shells are consistent with those of giant molecular clouds (GMCs), suggesting that the shells consist of swept-up, original GMC material. The influence of the expanding shell around the young Upper-Scorpius subgroup on the morphology of the Ophiuchus molecular clouds is investigated. The interaction of the shell with the Ophiuchus clouds accounts for the presence of a slow shock and for the shape of the elongated dark clouds connected to the ρ Oph dense cloud. The close passage of the trajectory of the runaway star ζ Oph by the center of the Upper-Scorpius shell, combined with the time-scale of formation of the shell strongly suggests that the star has originated in the Upper-Scorpius subgroup.

Key words: clusters: open and associations – Galaxy (the): solar neighbourhood – interstellar medium: bubbles – interstellar medium: clouds: Ophiuchus

1. Introduction

Stars interact with the surrounding medium through their photons and through their stellar winds. Early-type stars have long been known for their ionizing capacity through their strong ultraviolet flux. More recently, with the detection of strong stellar winds in their UV spectra, it was realized that the same early-type stars suffer severe mass loss. These stars therefore contribute a large amount of mechanical energy as well to the surrounding medium. Castor et al. (1975), and subsequently Weaver et al. (1977), and McCray & Kafatos (1987) calculated the effects of stellar winds on the ambient interstellar medium of early-type stars. They found that large bubbles will be formed around the most massive stars in an OB-association, which will merge to a so-called superbubble surrounding the whole association. After a few million years, supernovae will form an additional source of mechanical energy flux for the bubble (MacLow & McCray 1988).

The fourth galactic quadrant is characterized by the presence of a number of large, loop-like structures, which extend out of the plane to large latitudes ($|b| \leq 60^\circ$). The loops are beautifully seen in the photographic presentation of galactic H I by Colomb, Pöppel and Heiles (CPH, 1980), at velocities between -30 and 10 km s^{-1} (their Figs. 4 to 10, and 20). Such H I-structures have been discussed by Fejes & Wesselius (1973), Heiles & Jenkins (1976), Cleary et al. (1979), and Weaver (1978). Even farther out of the plane, the North Polar Spur, associated with the radio continuum structure Loop I, extends up to $b \approx 80^\circ$ (Berkhuijsen et al. 1971). An H I structure at $(l, b) \approx (300^\circ, -30^\circ)$ was proposed by Fejes & Wesselius to be the southern extension of the North Polar Spur. The large scale 408 MHz survey by Haslam et al. (1982) revealed the presence of strong radio continuum radiation inside the lower-latitude loop ($b \leq 60^\circ$). Diffuse X-ray emission was detected from gas associated with the inner-edge of the radio-continuum North Polar Spur (Burstein et al. 1977; Borken & Iwan 1977). The X-ray maps in bands $M1$, $M2$, and I of the survey by McCammon et al. (1983), covering energies between 440 and 1500 eV show furthermore that the lower-latitude loop also contains an inner edge of X-ray emission. The presence of the radio continuum and X-radiation associated with the inside of the H I structures supports the idea that the loop-like features surround the early-type stars. Weaver (1979) discussed the origin of the system of loops between $l = 270^\circ$ and $l = +30^\circ$ as being structures on the edge of an expanding shell around the Scorpio-Centaurus OB association (Blaauw 1964). We agree with this general picture, although the expansion velocity of 3 km s^{-1} adopted by Weaver does seem incorrect. The H I channel maps from Colomb et al. (1980) immediately reveal that the shell has an expansion velocity more like 10 to 20 km s^{-1} (see also the note added in proof to Heiles et al. 1980).

Cappa de Nicolau & Pöppel (1980, hereafter CdNP) discussed the presence of a large H I loop around Upper-Scorpius. The general picture proposed by these authors for the origin of the loop consists of an expanding shell formed by stellar winds and supernova explosions of stars in Upper-Scorpius. The results of the present paper agree with their general picture, however, the expansion velocity of 6 km s^{-1} CdNP derived for the shell is probably also an underestimate. Gas moving at larger velocities with respect to the systemic velocity of the shell will be shown likely to be part of the expanding structure. The knowledge of the physical properties of the stars in the different subgroups, based on the photometric observations described by de Geus et al. (1989, Paper I), enables us to make a comparison between the energy released by the stars and the kinetic energy of the shells. The

Send offprint requests to: E.J. de Geus (Maryland address)

availability of the large scale distribution of the dense material in the Ophiuchus region through the IRAS maps and our CO survey (de Geus et al. 1990, Paper II) allows the investigation of the interaction between the shell and the dense gas.

All three subgroups of the Scorpio-Centaurus OB-association are related to loop-like structures. In this paper the loops are investigated (Sect. 2.1), and their kinetic energies are compared with the expected total energy output from each subgroup (Sect. 2.2). The youngest subgroup, Upper-Scorpius, still contains a considerable amount of molecular material, and the interaction of the stars and the gas in this part of the association is complex. In Sect. 3 the morphology of the atomic and molecular gas and the dust will be described. The locations of the stars relative to the different structures are determined, in order to assess which stars are responsible for forming the H I-bubble in the Upper-Scorpius region. The relation between the elongated structures in the molecular cloud and the H I-bubble is discussed, and a model for the Ophiuchus/Upper-Scorpius region is constructed (Sect. 4). This paper is the fourth in a series of papers concerning the stars in the Scorpio-Centaurus OB association and their ambient interstellar matter. In Paper I photometric observations of the early-type stars were presented, in Paper II a ^{12}CO survey of the Ophiuchus dark clouds was described, and in Paper III (de Geus & Burton 1991) the distributions of atomic and molecular gas and dust in the Ophiuchus region were compared.

2. Large-scale structures; H I shells

2.1. Properties of the H I shells

The H I loops (or shells) that we want to focus on in this article are structures associated with the three subgroups of the Scorpio-Centaurus OB association (Blaauw 1964, Paper I). The largest one is the H I loop discussed by Weaver (1978), which is centered on $(l, b) = (320^\circ, 10^\circ)$, close to the position of the oldest subgroup of the Scorpio-Centaurus OB-association: Upper-Centaurus Lupus (UCL). The two smaller structures are located at $(l, b) = (295^\circ, 18^\circ)$ and $(l, b) = (347^\circ, 21^\circ)$ (see also CdNP). These loops each contain a subgroup of Sco-Cen within their boundaries: the Lower-Centaurus Crux group (LCC), and the (youngest) Upper-Scorpius group (US) respectively. The H I maps used to depict the structures discussed here were constructed from the surveys by Burton (1985), Heiles and Habing (1974), and Cleary et al. (1979).

Figure 1a shows the total integrated H I emission from the region between $l = 225^\circ$ and 75° , and $b = -60^\circ$ and $+60^\circ$, in which the loop-like structures surrounding the Upper-Centaurus Lupus region are seen. Figure 1b shows the same region as Fig. 1a, with the positions of the brightest stars in the three subgroups of Scorpio Centaurus drawn in. The positions of the H I loops are schematically shown in this figure.

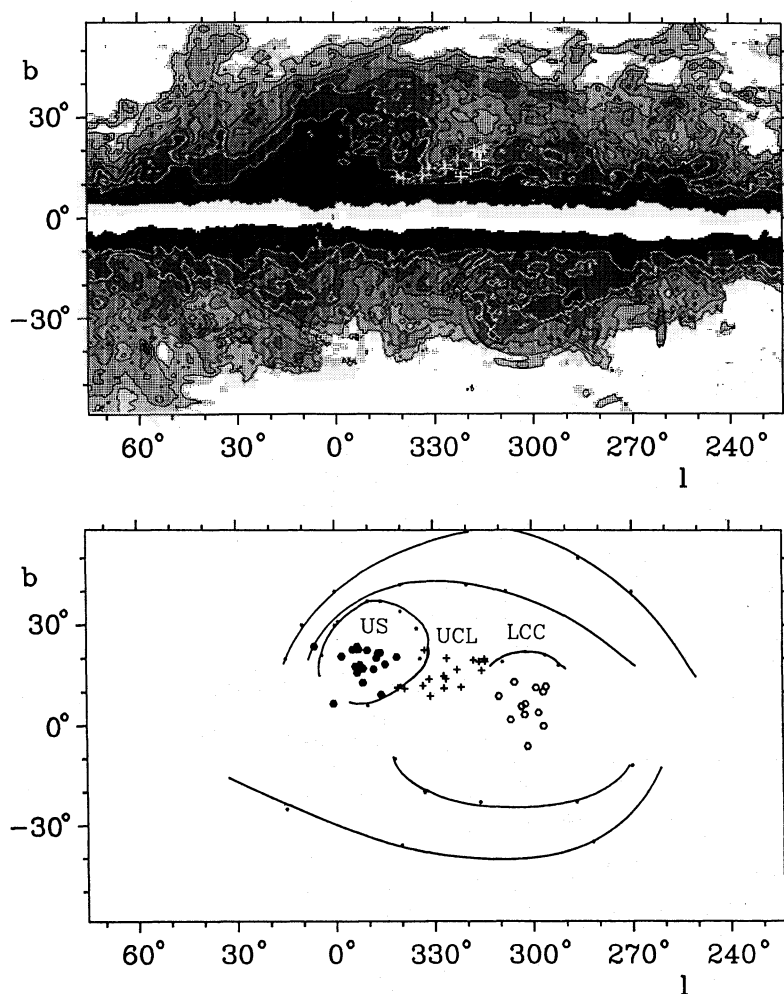


Fig. 1a. Map of the integrated H I column density in the region of Scorpio-Centaurus. The loop-like structures surrounding the Upper-Centaurus Lupus OB association extend up to 60° out of the plane. The positions of the stars and the loops are schematically drawn in Fig. 1b. The contour values are 40, 50, 65, 80, 95, and $140 \times 10^{19} \text{ cm}^{-2}$

Fig. 1b. Positions of the brightest stars ($< B3$) in the three subgroups of the Scorpio-Centaurus OB association are denoted by filled circles (Upper-Scorpius), pluses (Upper-Centaurus Lupus), and open circles (Lower-Centaurus Crux). The positions of the loops are drawn in schematically

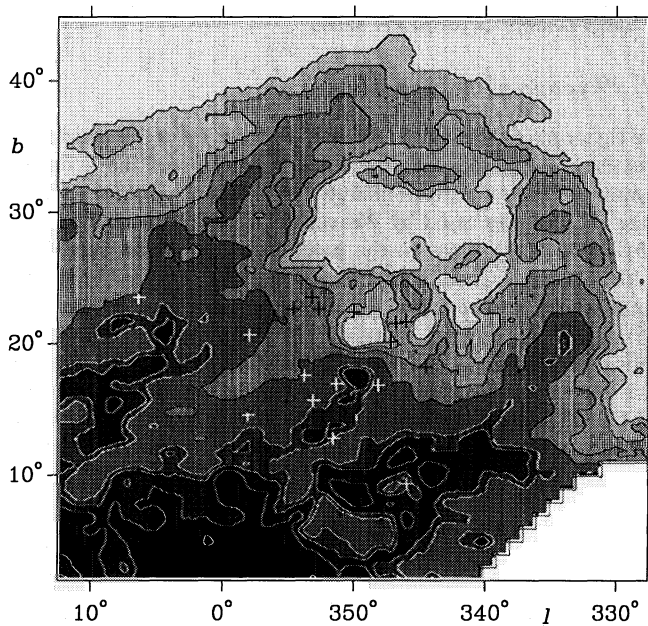


Fig. 2. Map of the integrated H I column density in the region of Ophiuchus/Upper-Scorpius, in the velocity interval $3 < v < 9 \text{ km s}^{-1}$. Note the presence of an H I loop surrounding the early-type stars in Upper-Scorpius (denoted as plusses)

Figure 2 shows the H I emission integrated over the range $3 < v < 9 \text{ km s}^{-1}$ in a smaller region between $l = 325^\circ$ and $+12^\circ$ and $b = -5^\circ$ and $+45^\circ$. This map clearly shows the loop around the Upper-Scorpius stars (the latter denoted as plusses). Figures 1a and 2 already indicate a relationship between the loops, or shells, and the subgroups. This impression is strengthened by the radio-continuum data from Haslam et al. (1982), and the X-ray maps presented by McCammon et al. (1983, notably the *M1*, *M2* and *I* bands) which show that the loops are associated with hot gas in their interior.

The structures surrounding the Upper-Scorpius and Upper-Centaurus Lupus subgroups show evidence of expanding motion and are therefore most likely parts of shells, which we will identify according to the subgroups: US- and UCL-shell. The H I loop near $(l, b) = (295^\circ, 18^\circ)$ does not show a clear relation to gas at either more positive or negative velocities with respect to the velocity of the loop. The kinematic structure of the H I gas shows no evidence for this loop actually being part of an expanding shell, but a shell center deduced from the curvature of the loop would give $(l, b) = (300^\circ, +8^\circ)$. The coincidence of this inferred center with the Lower-Centaurus Crux subgroup is interesting, and the H I-structure will therefore be referred to as the LCC-loop.

A number of properties of the H I shells can be derived from the channel maps and from the position-velocity maps of the H I. Figures 3 and 4 show the (b, v) maps along the centres of the shells. The dashed lines are fits to the data based on a simple geometric model of an expanding sphere (CdNP), assuming a snowplough model, with the expansion occurring in a gas layer of constant density and initially at rest.

The model gives the observed velocity of the sphere as a function of angle away from the line of sight to the expansion centre, and expansion velocity. The assumption that the ambient medium into which the sphere expands has a constant density is certainly violated. However the model can still be put to use to estimate the expansion velocity. The fit of the model to the data is

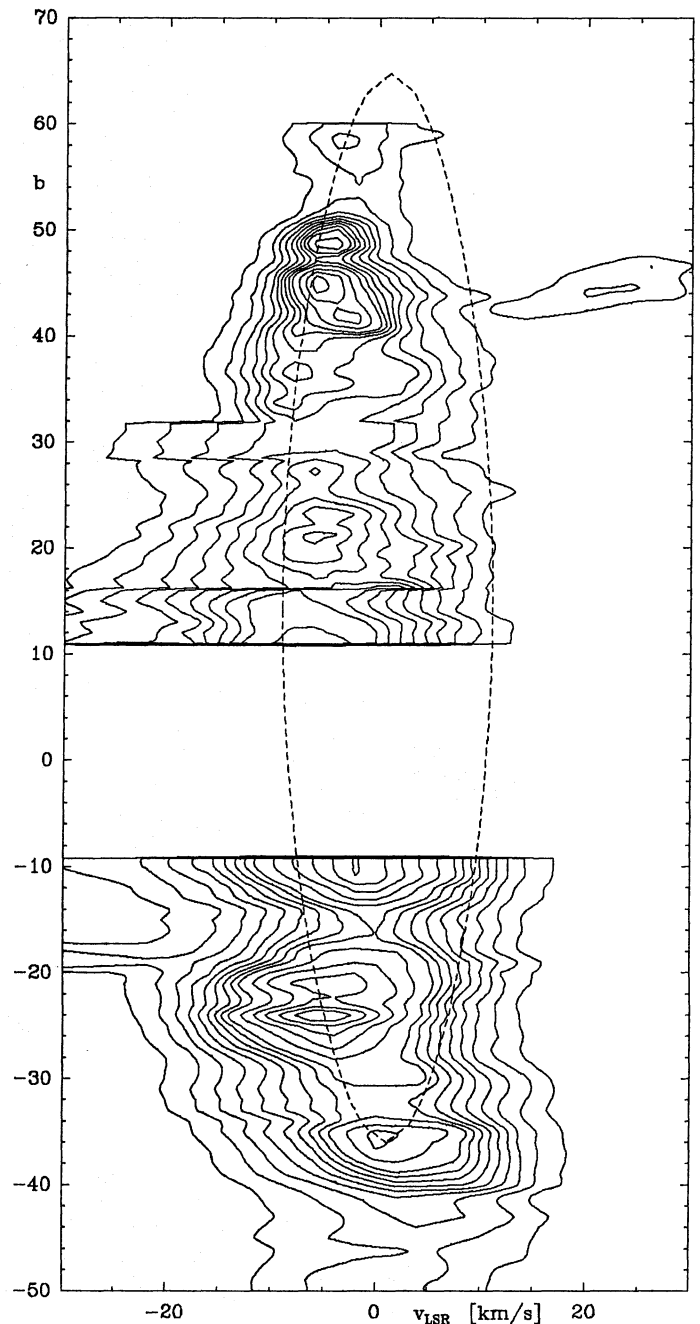


Fig. 3. $b-v$ map at $l = 320^\circ$ of the H I 21-cm observations showing the loop-like structures associated with the Upper-Centaurus Lupus subgroup. The data within 10° from the galactic plane are not included in the map. The dashed line is the best-fit of the model by Cappa de Nicolau & Pöppel (1986) to the data, of a shell with a radius of 50° , and an expansion velocity of 10 km s^{-1}

illustrated in Figs. 3 and 4 by showing a slice at one value of l for each of the loops. The H I structures that the model fits to, are part of the loop-like structures that can be clearly seen in the channel maps of the paper by Colomb et al. (1980). The best fits of the model to the position-velocity maps show that both the US-shell and the UCL-shell expand with a velocity of 10 km s^{-1} . These velocities are larger than the estimates by Weaver (1978) for the UCL-shell (3 km s^{-1}) and CdNP for the US-shell (6 km s^{-1}). From Figs. 1a and 2 the centres and radii of the shells were

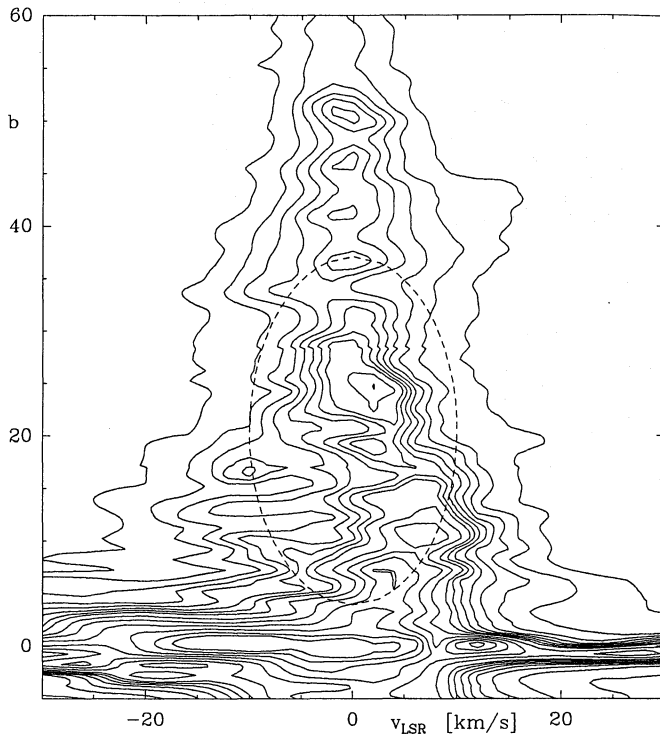


Fig. 4. $b-v$ map at $l = 347^\circ$ of the H I 21-cm observations showing the loop around the Upper-Scorpius subgroup. The dashed line is the model for a shell with a radius of 15° , and an expansion velocity of 10 km s^{-1}

derived, assuming the centres of the shells to be at the same distance as the subgroups. CdNP found a much larger radius for the expanding shell around Upper-Scorpius than the one proposed here. Their radius of 25° is actually close to our diameter. Their model of an expanding shell indeed fits the H I data (their Figs. 20a and b best for a shell radius of 25°). However, from Figs. 1a, 1b, and 2 it becomes clear that the gas components in their Figs. 20a and b at $b > 40^\circ$ and $l > 5^\circ$ respectively, that were included in the fit, are probably *not* associated with the US-shell

but with the UCL-shell. We therefore conclude that their estimate of the radius of the US-shell is too large. The total mass of the shells was determined using the conversion factor $1.823 \cdot 10^{18} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ to derive atomic hydrogen column densities from the integrated H I antenna temperatures. Derived properties are listed in Table 1. For further discussion of the shells see Sect. 2.3.

2.2. Energy sources

2.2.1. Energy output of early-type stars

The total mechanical energy output to the medium is contributed by the stellar winds of the stars still present in the field and by the stellar winds plus the mechanical energy caused by the supernovae of the massive stars that are no longer present. McCray & Kafatos (1987) described the evolution of bubbles around early-type stars towards superbubbles enveloping the entire OB-association. The evolution obviously starts with stellar-wind-blown bubbles surrounding the O- and B-type stars, which will merge to larger bubbles around several stars. A few million years after the formation of the association supernovae will start to go off inside the existing wind cavities, thereby adding more energy to the shells (McCray & Kafatos 1987; MacLow & McCray 1988). During the first 5 million years the stellar winds of the O-type stars and subsequently their supernova explosions dominate the energy input of the medium; later, supernova explosions of the B-type stars will take over the leading role. Weaver et al. (1977) and McCray & Kafatos (1987) give expressions for a number of observable parameters of a shell in terms of the energies of the stellar winds, the age of the association, and the original ambient density n_0 . We adopt their expressions for the radius, R_s , and expansion velocity, v_s , of a shell to calculate the effect of the Sco-Cen stars on the surrounding medium:

$$R_s = 269 \text{ pc } [L_{38}/n_0]^{1/5} t_7^{3/5}, \quad (1)$$

$$v_s = 15.8 \text{ km s}^{-1} [L_{38}/n_0]^{1/5} t_7^{-2/5}. \quad (2)$$

L_{38} is the total wind-energy flux in units of $10^{38} \text{ erg s}^{-1}$, n_0 is in cm^{-3} , and t_7 is the age of the association (or the star) in units of

Table 1. Properties of the H I shells

Subgroup	Centre l b	Extent l b	v_{sys} (km s^{-1})	v_{exp}	R (pc)	M 10^5 ($M_\odot$)	E_{kin} 10^{50} (erg)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
UCL shell	$320^\circ \pm 3^\circ$ $10^\circ \pm 3^\circ$	$265^\circ - +15^\circ$ $-40^\circ - +60^\circ$	1	10 ± 2	110 ± 10	3 ± 1	6 ± 2
US shell	$347^\circ \pm 2^\circ$ $21^\circ \pm 2^\circ$	$332^\circ - +2^\circ$ $+5^\circ - +37^\circ$	0	10 ± 2	40 ± 4	0.8 ± 0.3	1.7 ± 0.8
LCC loop	$300^\circ \pm 5^\circ$ $8^\circ \pm 5^\circ$	$285^\circ - 310^\circ$ $< +23^\circ$			35 ± 10	1.0 ± 0.5	

Notes: Column 1 gives the name of the subgroup with which the structure is found to be associated. Column 2 gives the approximate centre of the shell in galactic coordinates. Please note that for the LCC loop the center is inferred from the curvature of the H I-structure, on the, otherwise unsupported, assumption that it is part of an expanding shell. Column 3 gives the extent of the structures in galactic longitude and latitude, respectively. Column 4 shows the systemic velocities and column 5 the expansion velocity for the shells. Note that for the LCC-loop no evidence for expansion was found. Column 6 lists the radius of the shells and the loop, assuming that the distance to the centres of the structures is equal to the distance of the respective subgroups (de Geus et al. 1988, Paper I). Column 7 gives the mass of the H I structures, and in column 8 the kinetic energies of the US- and UCL-shells are listed

10^7 yr. The kinetic energy of the shell can then be derived assuming a snowplough model, i.e. an expanding shell whose momentum is conserved:

$$E_s = 3.8 \cdot 10^8 M_\odot (\text{km s}^{-1})^2 L_{38} t_7. \quad (3)$$

The energy of the shell is an important property, because it is directly proportional to the energy-flux from the stars. In order to determine the combined effects of stars that still exist and of stars that have disappeared, one has to simply calculate the separate energy contributions of each of the sources (using for t_7 the minimum of the age of the star and the subgroup age), and then add up the energies.

Subsequent supernovae will further increase the radius of the bubble. McCray and Kafatos (1987) give a general formula for the radius and expansion velocity of the bubble as a function of the age of the association, similar to Eqs. (1) and (2). They used a mean power delivered by the supernovae in the association, namely the total supernova energy output of all stars with mass $> 7 M_\odot$, averaged over the lifetime of a $7 M_\odot$ star. This approximation is valid for older associations, but it overestimates the energy considerably for the young associations, in which only a few supernovae have gone off. For the young associations, a better approximation is made by estimating the mean power delivered by supernova explosions so far: $L_{38, \text{SN}} = f N_{\text{SN}} E_{51} t_{\text{subgr}}^{-1}$, where N_{SN} is the number of supernovae that have gone off already, t_{subgr} is the age of the subgroup, and f is the fraction of the SN energy that is contributed to the kinetic energy of the shell ($f=0.2$: Weaver et al. 1977). This mean power can then be used as a constant luminosity and can replace L_{38} in Eqs. 1 and 2 when calculating the effect of supernova explosions. The combined effects of stellar winds and supernovae can be found by summing the energy fluxes:

$$R_s = 269 \text{ pc} [(L_{38, \text{W}} + L_{38, \text{SN}})/n_0]^{1/5} t_7^{3/5}, \quad (4)$$

$$v_s = 15.8 \text{ km s}^{-1} [(L_{38, \text{W}} + L_{38, \text{SN}})/n_0]^{1/5} t_7^{-2/5}, \quad (5)$$

and of course the energy:

$$E_s = 3.8 \cdot 10^8 M_\odot (\text{km s}^{-1})^2 (L_{38, \text{W}} + L_{38, \text{SN}}) t_7. \quad (6)$$

The total energy contribution of the stars to the shell can then be calculated, provided the total stellar content and the supernova history of the subgroups are known.

2.2.2. Stellar content of the subgroups

In order to assess the total initial stellar content of the subgroups, an initial mass function (IMF) has to be fit to the present day mass function (PDMF) of each of the subgroups. We adopted the shape of the IMF given by Miller and Scalo (1979), which is consistent with the one given by Garmany et al. (1982) for O-type stars outside the solar circle. The general form of this IMF is $dN = A M^{-B} d \log M$, where $B = 2.1$ for $M \geq 10 M_\odot$, $B = 1.5$ for $1 \leq M \leq 10 M_\odot$, and $B = 0.4$ for $M \leq 1 M_\odot$. The scaling factor A of the IMF was determined separately for each subgroup, by fitting the number of stars observed in a specific interval of mass. The limits of the mass interval are set by the maximum mass of stars still present, as predicted by the subgroup's age, and by the minimum mass at which the observations are still complete. The scaling factor A indicates the *richness* of the subgroup. The results for the three subgroups are listed in Table 2.

Column 3 of Table 2 lists the total number of stars in the subgroup, which is the integral of the IMF over the mass. This number is of course strongly dependent upon the lower-mass limit of the integral. Therefore the results for two lower-mass limits (0.1 and $2.0 M_\odot$ respectively) are listed. The lack of knowledge of the lower-mass limit to the stellar population of OB associations is a fundamental problem in the study of high- and low-mass star formation. In Paper I an attempt was made to use photometric observations to try and increase the information regarding stellar membership of the Scorpio-Centaurus OB association. Proper motion measurements of the stars are still the most accurate way of membership determination. In that respect the results of the astrometric satellite HIPPARCOS will be a very important tool to increase our knowledge of stellar membership in associations down to low masses.

Table 2. Properties of the stellar population of the Scorpio-Centaurus subgroups

Subgroup	Mass interval ($M_\odot$) (2)	N_{obs} (3)	A		N_{tot} (6)	M_{tot} ($M_\odot$) (7)
			$\geq 10 M_\odot$ (4)	$< 10 M_\odot$ (5)		
(1)						
U-S	6–13	19	6750	1700	3300 170	2350 780
U-CL	5– 9	23	6050	1500	2950 150	2100 690
L-CC	5–12	16	3800	950	1850 100	1300 430

Notes: Column 1 gives the name of the subgroup, column 2 gives the mass-interval used for scaling the IMF, column 3 lists the number of stars in that interval, and columns 4 and 5 show the resulting scaling factors of the initial mass function. Note that the scaling factor for masses $< 1 M_\odot$ is equal to the one for the interval between 1 and $10 M_\odot$. Integration of the given IMF over the whole range of masses gives an estimate of the total number of stars and the total mass of the stars (columns 6 and 7 respectively). This number critically depends on the lower-mass limit of the integration. The results for two lower limits are given: $0.1 M_\odot$, and $2 M_\odot$, respectively

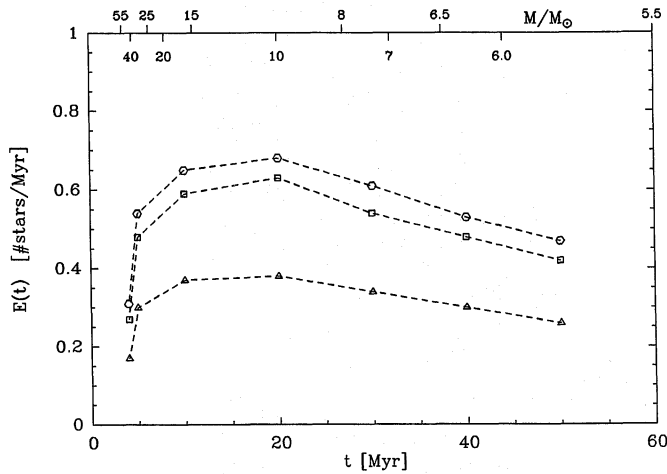


Fig. 5. Evaporation function for the three subgroups of the Scorpio-Centaurus OB association. The offsets between the curves of the subgroups are caused by the differences in the scales of their initial mass functions. The subgroup of richest content (Upper-Scorpius, open circles) has the highest evaporation function. The squares show the data for Upper-Centaurus Lupus, the triangles for Lower-Centaurus Crux. Note that the function peaks at $2 \cdot 10^7$ yr

The IMF combined with the lifetimes of the stars as functions of mass can be used to estimate the number of stars that have disappeared from the subgroups and become supernovae. The evaporation function, $E(t)$, introduced by Blaauw (1984), is defined as the number of stars that evolve away from the main sequence per million years. The main-sequence lifetime, $\tau_{\text{MS}}(M)$, as a function of mass was taken from Maeder (1981a and b). These lifetimes are consistent with the ones given by Lequeux (1979). $E(t)$ was calculated by convolving the IMF with $\tau_{\text{MS}}(M)$.

Figure 5 shows the evaporation function for the Scorpio-Centaurus subgroups. Note that the shape of the evaporation function is different from the one given by Blaauw (1984). He used the IMF of Garmany et al. (1982) over the whole mass interval, although it was calculated for $M \geq 10 M_{\odot}$. The IMF used here has a different slope below $10 M_{\odot}$. Figure 5 shows that the supernova frequency peaks at 20 Myr after the formation of the subgroup. For older associations the frequency of supernova explosions drops only very slowly (see also McCray & Kafatos 1987). Note that the supernova frequency as calculated by Blaauw, rises out to $5 M_{\odot}$. The lower-mass limit for stars to become a (type II) supernova is thought to be approximately $8 M_{\odot}$ (Woosley & Weaver 1986), above this mass the evaporation function derived here is similar to the one derived by Blaauw. The basic result of the paper by Blaauw (1984), concerning the production of pulsars, would not be influenced by the different shape of the evaporation function.

Integration of the evaporation function over the lifetime of the subgroup gives the total number of supernova explosions that may have occurred already (column 3 in Table 3). It should be realized that for the very youngest subgroups the uncertainties are considerable, because only the high-mass tail of the IMF is important there. If it is assumed that every supernova explosion has an energy of 10^{51} erg, this immediately gives the total SN energy-output delivered by the subgroup. The mean power is found by dividing the total SN-energy output by the age of the subgroup. About 20% of that power contributes to the kinetic energy of the shell.

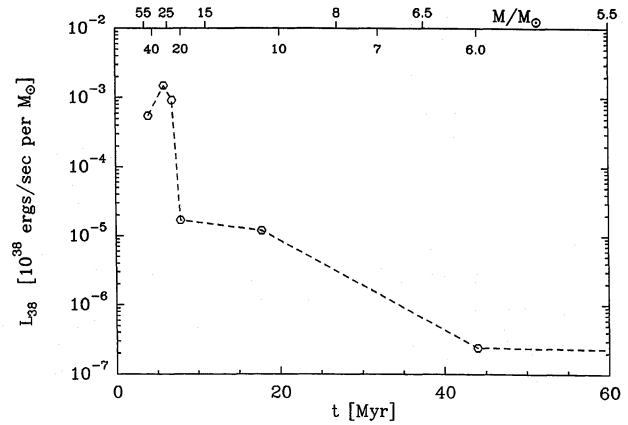


Fig. 6. Total mechanical luminosity per unit mass from the stellar winds of the stars in Upper-Scorpius. The curves for Upper-Centaurus Lupus and Lower-Centaurus Crux lie slightly below the one shown

2.2.3. Energy output of the subgroups

In order to calculate the total energy input of the medium by stellar winds, the IMF has to be convolved with the energies in the winds as a function of the stellar mass. Lamers (1988), Cassinelli & Lamers (1987), and Dupree (1981), give $\dot{M}$ and v_w for a range of spectral types, from which we determined $\dot{E}_{\text{wind}}$ as a function of mass. Figure 6 shows the resulting total mechanical luminosity per unit mass from the stellar winds, $L_{38,w}$, in units of $10^{38} \text{ erg s}^{-1} M_{\odot}$ for the Upper-Scorpius subgroup; the curves for the other two subgroups differ only by a small offset, and are therefore not drawn. The mass-loss rate drops very rapidly between O9 and B0, much more rapidly than the rise in the number of stars with decreasing mass.

It is therefore clear that the stellar-wind energy-flux of the subgroup is dominated by the O-type stars. In order to calculate the total effect of the stellar winds of the stars in a subgroup on a shell, a distinction has to be made between the stars still present and the stars disappeared. For the current stars $L_{38,w}$ is simply the integral of $L_{38,w}(M)$ over M , from M_{max} (the maximum mass still present in the subgroup) to some lower-mass cutoff. For the stars that have disappeared, the total contribution to the kinetic energy of the shell during their lifetime can be calculated for each star separately. The total kinetic energy of the shell due to the winds of stars past and present is simply the sum of the two.

For each of the three subgroups the different contributions to the surrounding medium can now be calculated. Table 3 lists per subgroup the number of stars that may have become supernova, and the contributions to the kinetic energy of the shell from the different sources. It is evident that in all three cases the contributions of stellar winds of stars still present can be neglected. This is of course due to the fact that in all three subgroups the stars have spectral types B0 or later, implying that very little stellar-wind power is left. In Upper-Scorpius one star of spectral type O9.5 is still present (ζ Oph), however, because it is a runaway star and therefore no longer inside the US-shell, its stellar wind energy was *not* included in the total.

Table 3. Energy output of the Scorpio-Centaurus subgroups

Subgroup	t_{nuc} (10^6 yr)	$\int_0^t E(t) dt$	$E_{\text{s}, \text{w}, \text{pr}}$ (10^{48} erg)	$E_{\text{s}, \text{w}, \text{pa}}$ (10^{50} erg)	$E_{\text{s}, \text{SN}}$ (10^{50} erg)	$E_{\text{s}, \text{tot}}$ (10^{50} erg)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
U-S	4–5	1 ± 1	1.2 ± 0.2	1.7 ± 0.6	1.0 ± 0.8	3 ± 2
U-CL	14–15	6 ± 3	0.6 ± 0.1	2.7 ± 0.8	6 ± 2	9 ± 3
L-CC	11–12	3 ± 2	0.6 ± 0.1	1.5 ± 0.4	3 ± 1	4 ± 2

Notes: Column 1 gives the names of the subgroups, column 2 gives the nuclear age of the subgroups (Paper I), and column 3 gives the integral of the evaporation function over the age of the subgroups, which indicates the number of stars that have disappeared from the subgroups. In columns 4 to 6 the contributions to the shell's kinetic energy by the different processes are listed: stellar winds of the presently seen stars, stellar winds of the stars evolved away, and supernova explosions respectively. Column 7 shows the total kinetic energy of a shell resulting from the actions of the stars listed in the table, as predicted by Eq. (6)

2.3. Origin of the H I shells

In this section the structures around the three subgroups of Scorpio Centaurus will be discussed separately.

2.3.1. UCL-shell

The complex of large H I loops extending far out of the plane in the fourth quadrant is part of an expanding shell surrounding the Upper-Centaurus Lupus group of stars, the oldest subgroup of the Scorpio-Centaurus OB association. The size of the H I shell ($r \sim 110$ pc) is larger than the extent of the early-type stars in the Upper-Centaurus Lupus OB association. This implies that all stars in the subgroup will have contributed to the kinetic energy of the shell. It is therefore reasonable to compare the total energy output of the subgroup (col. 7 in Table 3) with the kinetic energy of the shell (col. 8 of Table 1). The energy of the UCL-shell is equal to the calculated energy output of the stars to within 50%. It is therefore likely that the large H I shell in the fourth quadrant is a bubble blown by Upper-Centaurus Lupus. From the radius and the expansion velocity an age of 11 Myr is derived for the loop. This is consistent with the nuclear age of the stars in Upper-Centaurus Lupus of 15 Myr.

The large-scale structures found in the fourth quadrant have been the topic of a number of studies; especially the presence of the North Polar Spur (Berkhuijsen et al. 1971) has evoked considerable discussion. All neutral hydrogen structures in the fourth quadrant are characterized by having counterparts in hot gas, as evidenced by the 408-MHz maps from Haslam et al. (1982), and the X-ray maps from McCammon et al. (1983). The correspondence of the H I-loops below $b \approx 60^\circ$ with hot gas supports the model of formation of these structures by supernova explosions and stellar winds. The kinematical properties of the neutral gas associated with the North Polar Spur do not agree with that structure being part of the shell around Upper-Centaurus Lupus. We therefore agree with the picture sketched by Davelaar et al. (1980), who propose that the NPS is a remnant of a much more local supernova explosion, which may have gone off partly inside the nearest edge of the UCL-shell.

The distance from Upper-Centaurus Lupus to Upper-Scorpius is ~ 70 pc. At the current expansion rate the UCL-shell must have passed the region of Upper-Scorpius $4 \cdot 10^6$ yr ago. The nuclear age of the Upper-Scorpius subgroup is $5 \cdot 10^6$ yr. The close correspondence of these two numbers might suggest that massive star formation in Upper-Scorpius may have been ignited by the passage of the UCL-shell.

2.3.2. US-shell

The US-shell surrounds the young subgroup in Upper-Scorpius. The presence of the Ophiuchus molecular clouds in this area shows the surroundings of this shell to be very inhomogeneous. Furthermore, a number of the early-type stars in Upper-Scorpius are associated with H II regions (notably δ Sco, σ Sco, π Sco, and τ Sco), and “holes” in the H I distribution. Both these observations suggest that a number of the Upper-Scorpius stars are still embedded in, or at least surrounded by, the parent gas. This is particularly evident for some of the most massive stars (four of which are mentioned above), which means that these could not have contributed to the formation of the US-shell. The only stars of spectral type earlier than B2 that do not seem to be surrounded by molecular, atomic, or ionized gas are ω^1 and β^1 Sco and χ Oph. Of these three stars χ Oph is positioned far from the projected centre of the shell, and is therefore unlikely to be the cause of its formation. ω^1 and β^1 Sco are closer to the shell-centre, however the total kinetic energy contributed by the stellar winds of these stars is only $\sim 4 \cdot 10^{47}$ erg s $^{-1}$. This energy is almost three orders of magnitude lower than the kinetic energy of the shell, so the shell could not have been formed by the present-day population of the Upper-Scorpius subgroup. However, the integral of the evaporation function over the lifetime of the subgroup shows that it is likely that the initial population of Upper-Scorpius contained one star more than the present population. The most likely mass of that star is $40 M_\odot$, which implies a spectral type around O7, and a main-sequence lifetime between 4 and 4.5 Myr. Assuming that all stars in the subgroup are coeval, the supernova explosion of that most massive star would have occurred 1 to 1.5 Myr ago. The total contribution to the kinetic energy of the shell by the stellar wind and the supernova explosion of this star is simply the sum of columns 5 and 6 in Table 3. A comparison with the shell's kinetic energy shows that this one massive star could account for the energy of the bubble.

The present-day expansion velocity and the radius of the shell give an upper limit to the age of the shell of 2.5 Myr, consistent with the time (1 to 1.5 Myr) that has passed since the putative supernova explosion. The large velocity of the star ζ Oph has been suggested by Blaauw (1961) to be the result of a supernova explosion of a star in a binary, from which the secondary became the runaway. The trajectory and velocity of ζ Oph (Blaauw 1988 priv. comm.) take it to within 1° of the centre of the loop at a time between 1 and 2 Myr ago. The correspondence between the time scales and locations involved in the formation of the shell and the running away of ζ Oph gives a strong conjecture for a common origin, implying that the $40 M_\odot$ star had ζ Oph as a companion.

2.3.3. LCC-loop

Over its lifetime the Lower-Centaurus Crux subgroup is likely to have contributed more kinetic energy to the surrounding medium than the Upper-Scorpius group has, yet no evidence for an expanding shell is found. The only indication at all for an interaction of the stars with the surrounding medium is the projected positional correlation between the LCC-stars and the H I loop at $(l, b) \approx (297^\circ, 14^\circ)$. Because no evidence for expansion was found, only the information on the radius can help establish the relation between the H I-structure and the subgroup. The basic assumption made in this approach is that the H I-structure is indeed part of a shell. At a distance of 140 pc (i.e. the distance to the LCC-subgroup, Paper I) the radius of the loop is approximately 30 pc. The radius of a bubble that would have been blown by the present-day stars is $32 n_0^{-0.2}$ pc [Eq. (4)]. The radius of a bubble blown by stars that may have been members of the subgroup is $150 n_0^{-0.2}$ pc. Fitting these numbers to the actual radius of the loop-like structure around Lower-Centaurus Crux, the formation by the present-day population would imply an ambient density of 1 cm^{-3} , whereas formation by the initially present, more massive stars implies an ambient density of 10^3 cm^{-3} . The former density is characteristic of the diffuse interstellar medium, whereas the latter is characteristic of dark clouds, which is the more likely ambient density for stars in an OB association. It is clear that, beyond their positional correlation, no definitive statements can be made regarding the relationship between the small H I-loop and the LCC-subgroup.

Comparison of the properties of the shells and the loops with the total energy output from the subgroups of the association by stellar winds and supernovae, has shown that the stars provide enough energy to form the H I structures. The mass of the whole complex of H I-structures was found to be $3 \cdot 10^5 M_\odot$ (Table 1). This mass is typical for giant molecular clouds, which implies that the bulk of the GMC-material from which the Sco-Cen association formed has been deposited in the expanding shell. A comparison of the H I mass to the estimated total mass in the stars gives the star-formation efficiency in the Sco-Cen giant molecular cloud. The IMF-fit described in Sect. 2.2 gives the total stellar mass originally formed in the association. Although this number strongly depends on the cutoff at the lowest-mass end, the maximum star formation efficiency can be calculated, which is found to be 1.5%. This low value is consistent with the numbers generally quoted for the star formation efficiency in OB associations (Evans 1985), and for the ϱ Oph region in particular (Wilking & Lada 1985).

3. The Ophiuchus/Upper-Scorpius region

The Ophiuchus molecular clouds are characterized by a number of very elongated structures (Vrba et al. 1976; Wouterloot 1982; Paper II). These filamentary clouds have been suggested by Vrba (1977) to be formed due to the passage of a shock wave by the ϱ Oph dark cloud. The region of Ophiuchus and Upper-Scorpius has been studied extensively. For a review of the central ϱ Oph cloud, where star formation still continues, we refer to the paper by Klose (1986). Large-scale studies of the area, based on different tracers of the interstellar medium, were made by Sancisi & van Woerden (H I; 1970), Bronfman (CO; 1980), Wouterloot (OH; 1982), Olano & Pöppel (H I; 1981), Cappa de Nicolau & Pöppel (H I; 1986) de Geus et al. (CO; 1989 Paper II), and de Geus &

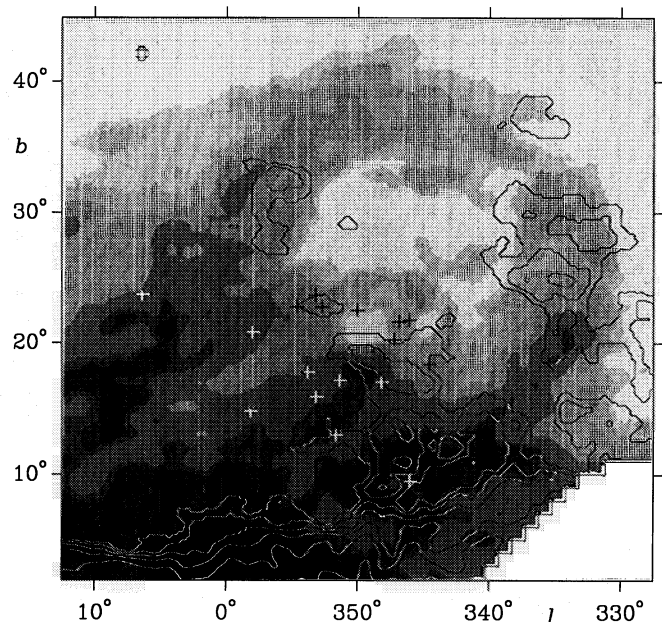


Fig. 7. Map of the integrated H I column density in the interval $-10 < v < -14 \text{ km s}^{-1}$ (contours), showing the -12 km s^{-1} feature, is plotted together with the total integrated H I column density from Fig. 2 (grayscale). The contour values are 11, 14, 20, 30, 50, and $90 \cdot 10^{19} \text{ cm}^{-2}$. The -12 km s^{-1} feature lies within the edges of the H I loop

Burton (dust and H I; 1991 Paper III). We are now able to combine the available large-scale information on the atomic, molecular and dust components, in order to construct a more complete picture of the processes that are responsible for shaping the ISM. In this section the Upper-Scorpius H I loop will be related to the morphology of the other tracers. From this comparison a model will be suggested describing the interaction of the Upper-Scorpius stars with the surrounding medium.

3.1. The -12 km s^{-1} -feature

From the $b-v$ map of the H I shell and the comparison with the model for an expanding spherical bubble, the approaching side of the H I shell was shown to have a velocity of -12 km s^{-1} . The H I-structure moving at this velocity was detected originally by Sancisi and van Woerden (1970). The full extent of the feature, and its confinement within the edges of the loop (Fig. 7) clearly shows its association with the H I loop.

The relation between the -12 km s^{-1} feature and the dark cloud is illustrated in Fig. 8, where the distribution of H I (contour representation) is plotted together with the IRAS $100 \mu\text{m}$ dust-distribution (shown as grayscale). The H I feature is clearly seen to avoid the dust clouds. This anti-correlation between the -12 km s^{-1} H I feature and the dense material suggests a physical relation. More-positive-velocity H I-gas from the shell is not seen to avoid the dust clouds so strongly. The fact that the fastest approaching gas in the shell is associated with the lowest densities of the Ophiuchus molecular cloud gas is consistent with conservation of momentum of an expanding shell, provided that the near edge of the shell is indeed interacting with the Ophiuchus gas. This confirms that the expanding shell is in the snowplough phase. Based on this, we conclude that the -12 km s^{-1} gas is in close interaction with the Ophiuchus dense clouds. If this is indeed the case, then the origin of the expanding shell, of which the

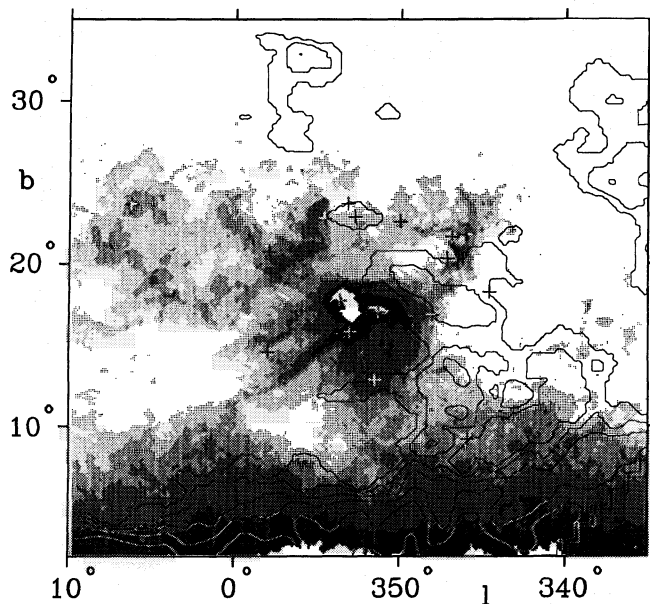


Fig. 8. Map of the integrated H I column density in the interval $-10 < v < -14 \text{ km s}^{-1}$ (contours), showing the -12 km s^{-1} feature, is plotted together with the distribution of the $100 \mu\text{m}$ intensities in the IRAS skyflux map (grayscale). The gray values are 40, 50, 65, 125, 200, and 300 MJy sr^{-1} . Note the anticorrelation between the dense material measured by IRAS, and the H I gas at the negative velocities. This supports the suggestion that the -12 km s^{-1} gas is part of the approaching edge of the shell, which interacts with the Ophiuchus gas

-12 km s^{-1} gas is the near side, has to be *behind* the bulk of the Ophiuchus molecular gas.

3.2. Presence of a slow shock

A number of absorption line studies towards stars in the Scorpio-Centaurus region are available for comparison with our large-scale studies of the gas and dust. These studies utilize lines from several different atoms, atomic ions, molecules and molecular ions. An interesting interpretation of Na I and Ca II absorption lines in terms of expanding shells around Sco-Cen is presented by Crawford (1991). The present paper will concern itself mostly with the CH molecule and its ion because of their interesting behaviour in a slow shock.

Elitzur & Watson (1980) predicted that in a low-velocity ($\approx 15 \text{ km s}^{-1}$) shock CH^+ and CH are enhanced in the shock and post-shock regions respectively. In their model the observation $v_{\text{CH}} > v_{\text{CH}^+}$ (which turns out to be the case for the Upper-Scorpius stars), implies that a shock is moving away from the Local Standard of Rest at the position of the Sun. Meyers et al. (1985) established the presence of a slow shock in the ISM from absorption line measurements of CH and CH^+ towards four stars in the Upper-Scorpius subgroup. Meyers et al (1985) interpreted the observations as being the result of a $+2 \text{ km s}^{-1}$ shock moving into pre-shock gas of -10 km s^{-1} , which they associated with the Ophiuchus molecular clouds. In their model the shock would have been caused by a supernova that occurred between the Sun and the Ophiuchus region. The main problem with this model is, that the -10 km s^{-1} gas into which the shock moves would have to be gas present in the Ophiuchus region, and we know that the gas in the Ophiuchus region as well as the stars in Upper-Scorpius have velocities near $+3 \text{ km s}^{-1}$. This discrepancy between the observed gas velocities and the gas velocities necessary to explain the CH

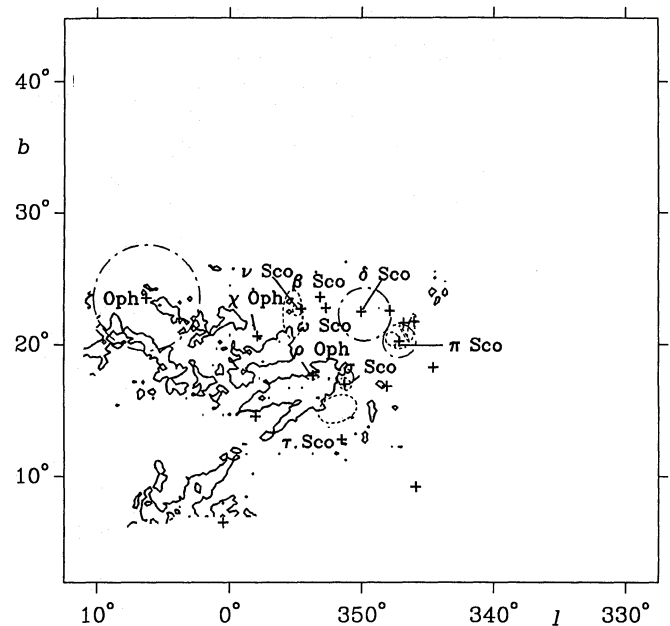


Fig. 9. Positions of the early-type stars in Upper-Scorpius, plotted as pluses, together with the lowest contour of the integrated CO intensity map (see Fig. 10). The positions of the H II regions around the stars are shown as the dash-dotted lines. The dotted lines outline the reflection nebulae in this region. Towards the named stars interstellar CH and CH^+ absorption line measurements are available, which are listed in Table 4

and CH^+ observations, requires careful reconsideration of the data.

New models for the formation of CH and CH^+ in slow shocks were constructed by Draine & Katz (1986) and Pineau des Fôrets et al. (1986), on the basis of magneto-hydrodynamic (MHD) calculations. Because of the presence of a magnetic field in the shock in their model, the charged particles (e.g. CH^+) reach the post-shock velocity much more rapidly than the neutrals (e.g. CH), resulting in a clear offset between their velocities. In their Fig. 4c, Draine & Katz (1986) give the relative velocities of the post-shock, CH, and CH^+ gas as a function of shock velocity. Their results can be summarized as follows:

$$v_{\text{CH}^+} \approx 0.85 (v_{\text{post}} - v_{\text{pre}}) + v_{\text{pre}}, \quad (4)$$

$$v_{\text{CH}} \approx 0.40 (v_{\text{post}} - v_{\text{pre}}) + v_{\text{pre}}. \quad (5)$$

In the MHD picture $v_{\text{CH}} > v_{\text{CH}^+}$ implies that the shock is moving *towards* the Sun. This is opposite to the direction found from the Elitzur and Watson model! In order to establish the properties of the slow shock as accurately as possible, the most recent values for the CH and CH^+ velocities were taken from the literature (CH: Danks et al. 1984, and Meyers et al. 1985; CH^+ : Lambert & Danks 1986). Where necessary, the CH velocities were corrected for the newly established rest wavelength of the CH A-X transition: $4300.3132 \text{ \AA}$ (Black and van Dishoeck 1988). This meant *adding* 0.54 km s^{-1} to the velocities given by Danks et al. (1984). Finally all velocities listed were converted to velocities relative to the Local Standard of Rest. The uncertainties in the CH and CH^+ velocities are of the order of 1 km s^{-1} . Table 4 gives the results for the seven lines of sight for which both the CH and CH^+ velocities are available. The positions of these lines of sight are shown in Fig. 9.

Table 4. Interstellar CH and CH⁺ velocities in lines of sight towards stars in Upper-Scorpius

Name	HD	v_{CH}^a (km s ⁻¹)	$v_{\text{CH}^+}^b$ (km s ⁻¹)	v_{post} (km s ⁻¹)	v_{pre} (km s ⁻¹)
(1)	(2)	(3)	(4)	(5)	(6)
β^1 Sco	144217	$1.9 \pm 0.7^\circ$	-3.0 ± 0.4	-4.6	6.1
ω^1 Sco	144470	-0.2 ± 0.7	-1.1 ± 0.4	-1.4	0.6
ν Sco	145502	1.8 ± 0.7	0.0 ± 0.4	-0.6	3.4
σ Sco	147165	$3.8 \pm 0.5^\circ$	3.3 ± 0.4	3.1	4.4
ϱ Oph	147933	2.9 ± 0.7	2.3 ± 0.4	2.1	3.4
χ Oph	148184	1.3 ± 0.7	1.3 ± 0.4	—	—
ζ Oph	149757	-0.1 ± 0.7	-0.9 ± 0.4	-1.2	0.6

Notes: ^a Unless indicated otherwise: Danks et al. (1984); ^b Lambert and Danks (1986); ^c Meyers et al. This causes v_{post} to be smaller, and v_{pre} to be larger for β and $\sigma\chi$

The pre-shock and post-shock velocities of the gas involved in the shock now follow upon substitution of the given CH and CH⁺ velocities in Eqs. (4) and (5). We note that these results are dependent on the angle between the shock and the cloud, projection effects can therefore affect these velocities. The resulting values are given in Table 4.

In the case of χ Oph the CH and CH⁺ velocities do not fit into a shock model. Note that for all stars except χ Oph $v_{\text{pre}} > v_{\text{post}}$, which implies that the shock(s) move(s) towards the Sun. The star ζ Oph (the runaway star) lies in a different part of the sky from the other 5, so that a comparison with the other stars does not seem appropriate. For the remaining stars the velocities of the pre-shock gas all lie in the range $0.5\text{--}6.5\text{ km s}^{-1}$, with $\bar{v}_{\text{pre}} = 3.7 \pm 2.0\text{ km s}^{-1}$. This pre-shock velocity is close to the velocity of the molecular material in the Ophiuchus clouds (Paper II). Because the Ophiuchus molecular cloud is the only aggregate of gas at that velocity in this part of the sky, and because it covers the whole area between π Sco and β Sco, we conclude that the pre-shock gas for the shocks observed in these directions is most likely the low-density extension of the Ophiuchus molecular clouds. None of the stars in Table 4 lies along the path of the dense material, therefore, it is likely that a considerable fraction of the observed CH is due to the shock, rather than pre-shock material.

We may be observing shocks caused by the stellar winds of the observed early-type stars themselves, or one large scale shock caused by a separate phenomenon. The -12 km s^{-1} structure which was argued in the previous section to be part of the near side of the expanding shell, is such a large scale phenomenon to which the shock can be ascribed. The collision of the -12 km s^{-1} feature and the Ophiuchus ($+4\text{ km s}^{-1}$) gas will cause a shock of the required speed to occur in the molecular cloud. This implies that the shock is caused by the interaction between the shell and the Ophiuchus molecular cloud gas into which it is expanding. Given the velocities of the two colliding clouds the jump-condition of the shock (notably pressure equilibrium) requires the ratio of the two cloud densities to be: $\varrho_{+4}/\varrho_{-12} = 2$. The density of the -12 km s^{-1} gas being very low, it is not surprising that no $+4\text{ km s}^{-1}$ gas in the line of sight towards for instance β^1 and ω^1 Sco was detected in the ^{12}CO -survey.

3.3. The H I shell and the molecular clouds

It was shown above that the approaching part of the H I shell is interacting with gas associated with the Ophiuchus molecular clouds. Only the low-density gas of the Ophiuchus clouds is

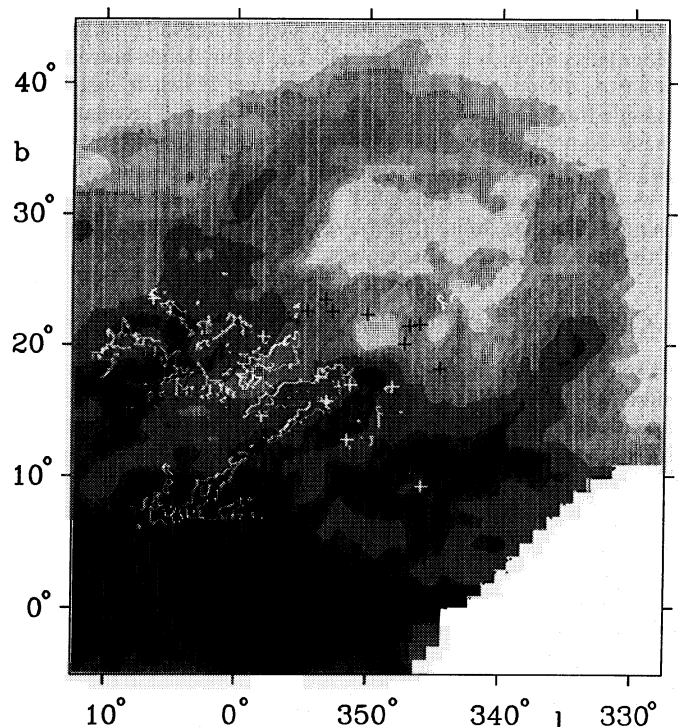


Fig. 10. The lowest contour (2 K km s^{-1}) of the integrated CO emission (de Geus et al. 1988b, Paper II) is plotted together with the integrated H I column density from Fig. 2. The elongated molecular clouds (at $l \approx 356^\circ$) lie in a gap in the H I loop, and are found to point in the direction of the center of the loop. Part of the H I is seen to curve around the molecular cloud structures. The CO clouds at the higher longitudes are associated with the high-longitude edge of the loop. The brightest stars in Upper-Scorpius are shown as pluses. Note that only part of the region shown in this figure was actually surveyed in CO. The boundaries of the CO survey are approximately $343^\circ < l < 10^\circ$ and $6^\circ < b < 26^\circ$

observed to be involved in this interaction. However, such low-density gas was not detected in the ^{12}CO survey, for instance, along the lines of sight towards the stars in Table 4.

It is of interest to compare the distributions of the ^{12}CO clouds which were detected, with the H I associated with the shell. Figure 10 shows a grayscale representation of the H I at velocities between 4 and 6 km s^{-1} . The ^{12}CO distribution is shown as the contours in the same picture. We draw attention to an elongated gap in the H I between $(l, b) = (353^\circ, 17^\circ)$ and $(10^\circ, 10^\circ)$. The high-

latitude end of the empty strip coincides with the ϱ Oph dark cloud, the densest part in the whole Ophiuchus complex. The lower-latitude boundary of the strip is delineated by the elongated ^{12}CO -complex 3 (Paper II). The opposite edge of the gap is traced by the top part of complex 2 and the string of clouds forming complex 5. The very close relationship between the CO features and the position and elongation of the gap in the H I suggests a physical relationship. The elongated ^{12}CO complexes 2, 3 and 5 all appear to point past the dense ϱ Oph cloud into the direction of the centre of the H I shell. This observation suggests that the structures were formed by the same shock that created the H I shell. We suspect that the encounter of the shock with a dense cloud, of which part is still seen as the ϱ Oph cloud, stripped material from the cloud, depositing it behind the cloud. After the passage of the shock the weak stellar winds of the B-type stars continue to accelerate the gas evaporating from the dense cloud, which may account for the small velocity gradients over the elongated clouds.

Of the remaining two ^{12}CO complexes (1 and 4), one part lies in the direction of the edge of the US-shell (complex 1 (T)), and the other parts lie outside the US-shell. The latter clouds however do lie in the direction of the edge of the larger US-shell, which lies outside the velocity-range represented in Fig. 10. The relation of these Complexes with the edges of the shells suggest that they might have formed as condensations in the shells. We note that the low-longitude edge of the shell is spatially correlated with the Lupus molecular clouds (Murphy et al. 1986), suggesting a similar formation model for these clouds.

3.4. Early evolution of the Ophiuchus/Upper-Scorpius region

A self-consistent description of the interaction of stars and interstellar matter in the general region may be based on the distribution of the different tracers of the interstellar matter in Ophiuchus, and their relationship with the stars in Upper-Scorpius. Figure 11 schematically shows the relative positions of the interstellar components and the stars, in the form of a slice at constant longitude through the centre of the US-shell.

The region was originally filled with gas at velocities comparable to the present-day velocity of the ϱ Oph cloud. The ϱ Oph cloud seen today is part of a once bigger cloud, which was a "clump" in the general Ophiuchus gas. Stars are distributed throughout the region, and some are still embedded in the denser clumps. The most massive star is the primary component of a binary. All early-type stars are blowing bubbles around themselves, and ionizing the insides. The most massive star ($\sim \text{O7}$) blows the largest bubble during its lifetime, and, after dying as a supernova, adds more kinetic energy to the shell. The massive star being one of a binary, the supernova explosion of the primary star gravitationally released the secondary, to become the fast-moving "runaway" star ζ Oph.

The bubble expands with a velocity of approximately $10\text{--}15\text{ km s}^{-1}$ depending on the local density of the ambient medium. The shell has a contact discontinuity on the inside (dashed line in Fig. 11). The outer edge of the shell consists of a shock front moving into the ambient medium. The region between these two edges contains the swept-up material of the shell. The -12 km s^{-1} feature is part of the edge of the shell nearest to the Sun, which has passed through gas of relatively low density, and therefore still contains the largest velocity (consistent with the snowplough model). In the schematic side view of the region (Fig. 11) this feature forms the left side of the shell. The -12 km s^{-1} gas shocking the ambient, original Ophiuchus gas is responsible for the CH and CH^+ absorption lines seen towards the

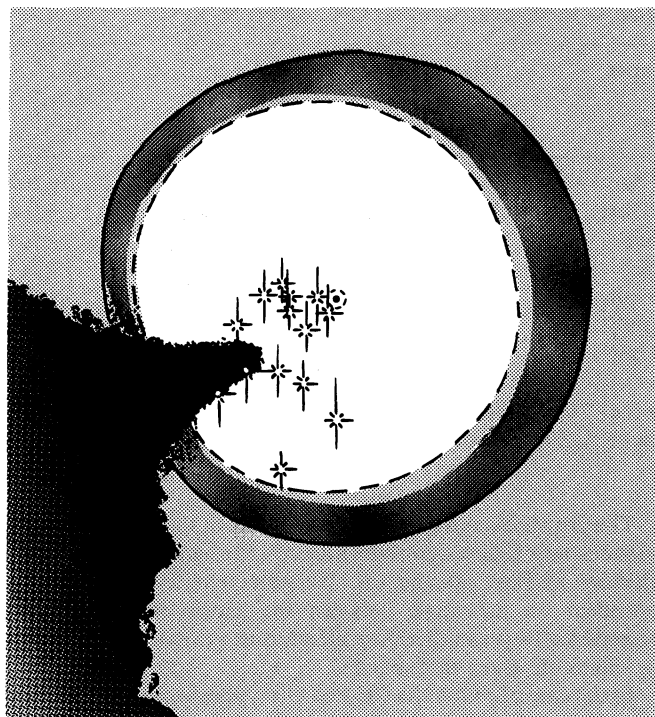


Fig. 11. The relation between the Ophiuchus gas and the expanding shell is schematically represented in the form of a side view of a slice at constant longitude through the shell. Earth lies to the left in this picture. The inside of the shell contains hot gas, and is connected to the shell by a contact discontinuity, denoted by the dotted line. The shell consists of swept up gas, and the outer edge is a shock front (the thick line) expanding into the ambient medium (denoted by the lowest graylevel), which has a velocity of approximately $+3\text{ km s}^{-1}$. The -12 km s^{-1} feature is the left-most edge of the shell. The result of the interaction of the shell with the dense ϱ Oph cloud is shown as the "nose" sticking into shell from the lower left. The position of the massive star, whose stellar wind and supernova explosion formed the shell, is shown as the circled dot

stars located behind the shock. The encounter of the expanding shell with the dense ϱ Oph clump prohibited the continuation of the shell behind the clump and hence resulted in the gap in the H I shell. This encounter may also have triggered the continuing star formation in the ϱ Oph cloud. The passage of the shock caused molecular gas to be swept off the clump, which was then deposited as elongated clouds to the side of the region apparently avoided by the shell (the so-called streamers, CO complexes 2, 3 and 5 in Paper II). This is depicted in Fig. 11 by the "nose" sticking into the bubble.

4. Conclusions

The large scale H I structures that dominate the appearance of the fourth galactic quadrant outside the galactic plane have been shown to be closely related to the Scorpio-Centaurus OB association. Three H I structures have been identified as associated with the three subgroups of Scorpio-Centaurus. Evidence for expanding motion was found from the $b-v$ maps of the structures around Upper-Scorpius and Upper-Centaurus Lupus. The H I loop around Lower-Centaurus Crux is not connected to gas at different velocities. The kinetic energies of the two shells were found to be $2 \cdot 10^{50}$ and $6 \cdot 10^{50}$ erg. The initial mass function was fit to each of the subgroups to allow an estimate of the total energy

output. The Upper-Scorpius and Upper-Centaurus Lupus subgroups were found to have a similarly rich stellar content, whereas Lower-Centaurus Crux has a poorer one. From a comparison of the IMF to the present-day mass function the number of massive stars that have evolved away was estimated. Hence the total energy from the stellar winds and the subsequent supernova explosions that have occurred in each subgroup was calculated. The total energy output of the Upper-Scorpius and Upper-Centaurus Lupus subgroups was found to be consistent with the kinetic energy of their shells. The H I structures are therefore indeed likely to be parts of wind- and supernova-blown shells around the stellar aggregates. It was shown that the energy contribution to the US-shell is due in equal amounts to the stellar wind and supernova-explosion of a massive star. For the UCL-shell the largest contribution (70%) is made by supernovae.

The properties derived for the US-shell differ from those derived by CdNP. The radius of the loop was argued to be half of that found by these authors. The difference is due to the fact that H I structures, assumed by CdNP to be part of the US-shell, were here suggested to be part of the much larger shell around the Upper-Centaurus Lupus subgroup. Furthermore, the expansion velocity derived for the US-shell is larger than the one found by CdNP. It is therefore not possible to compare estimates of the timescales involved in the formation of the shell that were made by CdNP with those derived here. The main conclusion by CdNP regarding the formation of the shell by stellar wind(s) and supernova(e), however, is confirmed by the present work.

Comparison of the atomic and molecular gas and dust in the Ophiuchus/Upper-Scorpius region revealed the dominating influence of the US-shell on the morphology of the region. The presence of a slow shock is indicated by CH and CH⁺ absorption line observations. The shock is likely to have been caused by the collision of the shell with the original Ophiuchus cloud gas. A conspicuous gap in the H I loop was found on the side of the dense ϱ Oph cloud opposite to the position of the early-type stars. The edges of the gap coincide with the elongated molecular clouds. The whole system of the ϱ Oph dense cloud and the connected elongated molecular clouds pointing away from the centre of the shell gives the distinct impression of a structure shaped by the passage of a shock wave. After the supernova explosion of the massive star only weaker stellar winds continue to accelerate the gas evaporating from the dense cloud, which might account for the lack of large velocity gradients over the elongated clouds. The close passage of the trajectory of the runaway star ζ Oph to the centre of the shell suggests that it might have been the secondary companion in a binary with the massive star whose death as a supernova ultimately dominates the morphology of the Ophiuchus/Upper-Scorpius region.

Acknowledgements. The author is grateful to Drs. Blaauw, Burton, de Zeeuw, and van Dishoeck for continued interest and careful reading of the manuscript. Drs. Draine and Heiles are thanked for useful discussions. The author owes thanks to Dr. Deul for making the H I maps available. Dr. Icke constructed the schematic model for the Ophiuchus region. The author further acknowledges financial support through NSF grant AST-8918912 and NASA grant NAG 5-1736.

References

- Berkhuijsen E.M., Haslam C.G.T., Salter C.J., 1971, A&A 14, 252
 Blaauw A., 1961, Bull. Astron. Inst. Neth. 15, 265
 Blaauw A., 1964, ARA&A 2, 213
 Blaauw A., 1984, in: Birth and Evolution of Massive Stars and Stellar Groups, Boland W., van Woerden (eds.). Reidel, Dordrecht, p. 211
 Black J.H., van Dishoeck E.F., 1988, ApJ 331, 986
 Borken R.J., Iwan D.C., 1977, ApJ 218, 511
 Bronfman L., 1980, M. Sc. Thesis, University of Chile
 Burstein P., Borken R.J., Kraushaar W.L., Sanders W.T., 1977, ApJ 213, 405
 Burton W.B., 1985, A&AS 62, 315
 Cappa de Nicolau C.E., Pöppel W.G.L., 1986, A&A 164, 274 (CdNP)
 Cassinelli J.P., Lamers H.J.G.L.M., 1987, in: Exploring the Universe with the IUE Satellite, Kondo Y. (ed.). Reidel, Dordrecht, ASSL 129, p. 139
 Castor J., McCray R., Weaver R., 1975, ApJ 200, L107
 Cleary M.N., Heiles C., Haslam C.G.T., 1979, A&AS 36, 95
 Colomb F.R., Pöppel W.G.L., Heiles C., 1980, A&AS 40, 47
 Crawford I.A., 1991, A&A 247, 183
 Danks A.C., Federman S.R., Lambert D.L., 1984, A&A 130, 62
 Davelaar J., Bleeker J.A.M., Deerenberg A.J.M., 1980, A&A 92, 231
 de Geus E.J., de Zeeuw P.T., Lub J., 1989, A&A 216, 44 (Paper I)
 de Geus E.J., Bronfman L., Thaddeus P., 1990, A&A 231, 137 (Paper II)
 de Geus E.J., Burton W.B., 1991, A&A 246, 559 (Paper III)
 Draine B.T., Katz N., 1986, ApJ 310, 392
 Dupree A.K., 1981, in: Effects of Mass Loss on Stellar Evolution, IAU Colloquium 59, Chiosi C., Stalio R. (eds.). Reidel, Dordrecht, p. 87
 Elitzur M., Watson W.D., 1980, ApJ 236, 172
 Evans N.J., 1985, in: Protostars and Planets II, Black D.C., Matthews M.S. University of Arizona Press, Tucson
 Fejes I., Wesselius P.R., 1973, A&A 24, 1
 Garmany C.D., Conti P.S., Chiosi C., 1982, ApJ 263, 777
 Haslam C.G.T., Salter C.J., Stoffel H., Wilson W.E., 1982, A&AS 47, 1
 Heiles C., Habing H.J., 1974, A&AS 14, 1
 Heiles C., Jenkins E.B., 1976, A&A 46, 333
 Heiles C., Chu Y.-H., Reynolds R.J., Yegingil I., Troland T.H., 1980, ApJ 242, 533
 Klose S., 1986, Ap&SS 128, 135
 Lambert D.L., Danks A.C., 1986, ApJ 303, 401
 Lamers H.J.G.L.M., 1988, in: Mass Outflows from Stars and Galactic Nuclei, Bianchi L., Gilmozzi R. (eds.). Kluwer, Dordrecht, ASSL 142, p. 39
 Lequeux J., 1979, A&A 80, 35
 MacLow M.-M., McCray R., 1988, ApJ 324, 776
 Maeder A., 1981a, A&A 93, 102
 Maeder A., 1981b, A&A 102, 401
 McCammon D., Burrows D.N., Sanders W.T., Kraushaar W.L., 1983, ApJ 269, 107
 McCray R., Kafatos M.C., 1987, ApJ 317, 190
 Meyers K.A., Snow T.P., Federman S.R., Breger M., 1985, ApJ 288, 148
 Miller G.E., Scalo J.M., 1979, ApJS 41, 513
 Murphy D.C., Cohen R., May J., 1986, A&A 167, 234
 Olano C., Pöppel W.G.L., 1981, A&A 95, 316

- Pineau des Fôrets G., Flower D.R., Hartquist T.W., Dalgarno A., 1986, MNRAS 220, 801
- Sancisi R., van Woerden H., 1970, A&A 5, 135
- Sivan J.P., 1974, A&AS 16, 163
- Vrba F.J., 1977, AJ 82 (3), 198
- Vrba F.J., Strom S.E., Strom K.M., 1976, AJ 81 (11), 958
- Weaver H., 1979, in: The Large-Scale Characteristics of the Galaxy, IAU Symposium 84, Burton W.B. (ed.). Reidel, Dordrecht, p. 295
- Weaver R., McCray R., Castor J., Shapiro P., Moore R., 1977, ApJ 218, 377 (Erratum 220, 742)
- Wilking B.A., Lada C.J., 1985, in: Protostars and Planets II, Black D.C., Matthews M.S. University of Arizona Press, Tucson
- Woosley S.E., Weaver T.A., 1986, ARA&A 24, 205
- Wouterloot J.G.A., 1982, A&A 135, 32