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ASTRONOMY AND ASTROPHYSICS

OH observations of the Ophiuchus complex

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Summary. The molecular clouds near the Upper Scorpius association have been mapped in OH with the Dwingeloo telescope. The main lines were observed over an area of 48 square degrees and at four positions we also made satellite line observations. We derive a mass of the complex of about $(12 \pm 10)\,10^3 M_\odot$. The mean density within the clouds is about 500 cm^{-3}, but within the complex as a whole it is much smaller. The radial velocity is constant along the streamers and a velocity gradient exists perpendicular to them.

Key words: OH emission – molecular clouds – Ophiuchus region

1. Introduction

The complex of dark clouds near ϱ Ophiuchi is one of the nearest regions of recent star formation. The dark clouds in this area have been studied and catalogued by Barnard (1927), Khavtassi (1960) and Lynds (1962). A sketch of the area is given in Fig. 1, which is adopted from Khavtassi. Table 1 gives cross references of the names of the different clouds. The whole region can be seen on plate 5 in the Atlas of the Northern Milky Way (Ross and Calvert, 1934). Some of the dark clouds have a very elongated structure, often referred to as "streamers", although it remains to be proven that they really show or were formed through streaming motions. The clouds are related to the Sco OB 2 or Upper Scorpius association, the youngest subgroup of the Scorpio Centaurus association. Blaauw (1964) summarizes much work on this association. He derived a distance of about 170 pc to Sco OB 2. Garrison (1967) arrives at the same result and we shall adopt this value throughout this paper.

Observations of molecules within a limited area have been made by various authors, e.g. Encrenaz et al. (1975) and Myers et al. (1978). Apart from a few OH observations by Crutcher (1973) and the H_2CO observations along the streamers by Heiles and Katz (1976) all molecular observations concern a small area of about 0.8 square degrees. A large-scale molecular survey is needed to study the overall structure of this star forming region. Therefore we made the observations of OH covering a large area of sky that are described in the present paper.

We give in Sects. 2 and 3 a discussion of the method of observation and of the observational results. In Sect. 4 an analysis is made of the OH observations. The velocity structure of the cloud complex is discussed in Sect. 5 and the relation of the clouds with present and past star formation is discussed in Sect. 6. In Sect. 7 we discuss the morphology of the whole region.

Table 1. Cross references of the most important clouds in the Ophiuchus area. Kh = Khavtassi (1960); L = Lynds (1962); B = Barnard (1927)

Kh 519 = L 1672 = B 229
Kh 527 = L 1675
Kh 536 = L 1676
Kh 538 = L 1680 + L 1687
Kh 547 = L 1681
Kh 556 = L 1709
Kh 563 = L 1712 + L 1729 + L 1761 + L 1763 = B 44 + B 238
Kh 567 = L 1739 + L 1740
Kh 569 = L 1717 + L 1719 + L 1752 + L 1757
L 1752 = B 43
Kh 584 = B 46
Kh 585 = B 45 = L 1744 + L 1755 + L 1765
Kh 596 = B 47 + B 51
B 46 + B 47 + B 51 = total of 12 Lynds clouds
Heiles' cloud 4 = L 1681
Streamer 1 = Kh 556 + Kh 567 + Kh 585
Streamer 2 = Kh 563

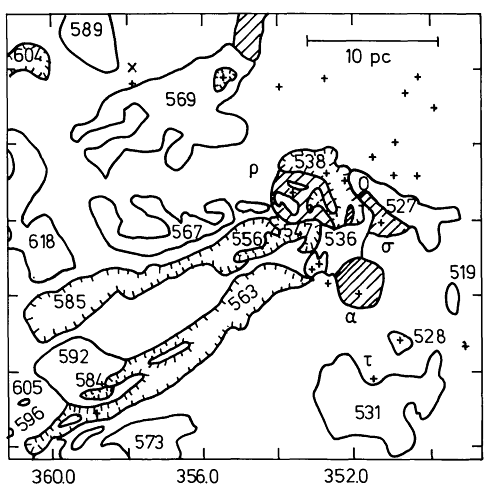

Fig. 1. A sketch of the Ophiuchus area from the atlas of dark clouds by Khavtassi (1960). The hatched areas are reflection nebulae, the dashed lines indicate heavy obscuration. The plusses are stars of the Upper Scorpius association

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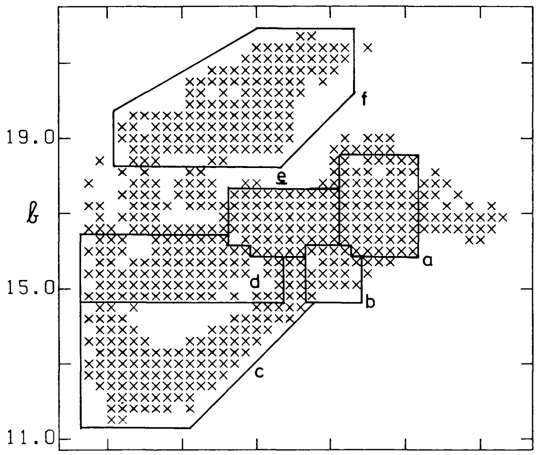

Fig. 2a–f. The positions observed in OH (*crosses*), divided over regions (**a–f**) that are discussed separately

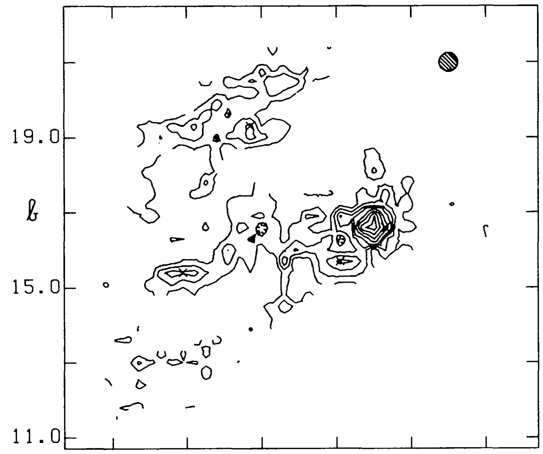

Fig. 3. Contour map of the peak antenna temperature at 1667 MHz. Contour values are 0.04, 0.06, 0.08, 0.10, 0.14,... K. Crosses indicate positions where satellite lines have been observed

2. Observations

The Ophiuchus clouds were observed with the 25 meter Dwingeloo telescope in the mainlines of OH at 1665 and 1667 MHz in the same manner as the Taurus complex (Wouterloot and Habing, 1983). Observational parameters are described there. The rms noise in each spectrum was about 0.02 K. The declination of Ophiuchus is so low that only 8 positions per day could be observed and a fully sampled, unbiased survey was not possible. Therefore we selected the areas to be observed from Khavtassi's (1960) atlas of dark clouds. The positions observed are indicated in Fig. 2. The total area observed is 48 square degrees. Some of the positions which showed up as peaks in our OH distribution were subsequently observed in the satellite lines at 1612 and 1720 MHz. These observations were made in the frequency switched mode with an integration time of 4 h (rms moise about 0.01 K) and the same resolution as the main lines (0.9 km s^{-1}).

3. Observational results

The distribution of the peak antenna temperature for the 1667 MHz line is shown in Fig. 3. One can distinguish two main areas of OH emission. The first area contains the ϱ Ophiuchi cloud and the streamers that emerge from it. In the second area are the clouds around (358°, +19°), associated with Kh 569 (see Fig. 1). The most striking feature in the first area is the relatively strong peak of about 0.28 K near the center of the ϱ Oph cloud. In addition there are a number of less intense peaks of about 0.10 K, all embedded in an extended structure of 0.05 K or less. In some places the observations did not reach the cloud edges, but judging from the optical appearance of the cloud on the POSS prints and from incidental observations outside the mapped area, it is unlikely that the low intensity cloud extends much beyond the boundaries in Fig. 3. Of the two streamers, the upper one (streamer 1, see Table 1 and Fig. 1) was detected over its full length, whereas the lower one (streamer 2) was only detected at its very beginning and rather marginally at a few positions further "downstream". The second area, containing the Kh 569 complex, is less prominent on the POSS prints. This implies more foreground stars or less extinction. However it showed up in the OH lines over quite a large area as can be seen in Fig. 3.

As is the case for the Taurus region, the Ophiuchus complex contains no maser sources stronger than 0.4 Jy.

4. Analysis

4.1. Analysis of satellite line observations

We have made satellite line observations at the four positions indicated in Fig. 3. Table 2 summarizes the line parameters. The uncertainties in $T_{A,i}$ are about 0.015 K. The methods of analysis are described elsewhere (Wouterloot and Habing, 1983; Wouterloot, 1981). The observed quantities are the antenna temperatures $T_{A,i}$ ($i=1$ to 4 for 1612 to 1720 MHz) and linewidths ΔV_i. Derived quantities are excitation temperatures $T_{ex,i}$, optical depth τ_i, $DT \equiv T_{ex,2} - T_{ex,3}$ and column density N_{OH}. (We estimated the excess (galactic) background temperature following Heiles (1969) from the maps of Seeger et al. (1965) and obtained a mean value of about 0.9 K. It changes systematically from 1 K at $b=10°$ to 0.75 K at $b=20°$. We assume that all non-thermal radiation originated behind the clouds. This may not be true in this area. In view of this uncertainty we did not incorporate a change with latitude, so we adopted the mean value. Together with the cosmic background this means $T_{BG}=3.6$ K.

The results of the analysis are summarized in Table 3. The first position is somewhat outside the center of the cloud. The filling factor F, assumed to be 1.0, may be smaller if $\tau_3 \simeq 1.6$, at the high side of the permitted interval. The limits for DT then are the same ($DT \leqq 0.5$ K). Turner (1973) observed a nearby position which he called 4C (353.05, +16.67), at the center of the ϱ Oph cloud. If we assume that the OH column density at this position is not smaller than at position 1, which is situated at some distance from the cloud center, a negative DT of a few times 0.1 K is the most probable.

At the third position the main lines point toward a low τ_3. However, if $\tau_3 \leqq 0.8$ or $DT \geqq 0.1$ K, the 1720 MHz line is predicted to be much weaker than observed.

4.2. Analysis of main line observations

We divided the observed area somewhat arbitrarily according to their OH outlines into 6 regions (indicated in Fig. 2). The main results of the analysis are displayed in Table 4. The linewidths were

Table 2. Values of the observed parameters of the four ground state lines at selected positions

	l	b	$T_{A,1}$ / V / ΔV	$T_{A,2}$ / V / ΔV	$T_{A,3}$ / V / ΔV	$T_{A,4}$ / V / ΔV	I_2	I_3
1.	352.7	16.6	−0.022 K	0.097	0.163	0.080	0.167 K km s^{-1}	0.313
			3.2 km s^{-1}	3.6	4.0	3.6		
			1.5 km s^{-1}	1.7	1.8	1.7		
2.	353.9	15.7	−0.019	0.106	0.092	0.064	0.178	0.203
			4.2	4.1	4.3	4.2		
			0.5	1.5	1.9	1.5		
3.	356.3	19.3	0.02	0.040	0.091	0.032	0.126	0.190
			1.4	0.8	1.4	1.0		
			1.2	2.5	1.7	1.5		
4.	358.1	15.4	−0.016	0.061	0.084	0.068	0.073	0.081
			2.8	2.6	3.0	2.5		
			1.0	1.8	1.5	1.9		

Table 3. Derived parameters

	τ_3	$T_{ex,3}$ K	N_{OH} 10^{14} cm^{-2}	$T_{ex,1}$ K	$T_{ex,4}$ K	DT
1.	1.0±0.6	3.9	15±10	3.3±0.3	6±2	≦0.5
4C	0.8±0.2	5.5	15	3.6	5	−0.2
2.	2 ±1	3.7	30±10	3.5	4.2	≦1.0
3.	1 ±0.5	3.8	15± 0.5	3.5	4.0	0
4.	1.5±1	3.7	20±10	3.3	4.4	≦0.4

Table 4. Mean OH parameters in different parts of the complex

Region	τ_3	ΔV km s^{-1}	$T_{ex,3}$ K	$N_{OH,min}$ cm^{-2}	$N_{OH,max}$ cm^{-2}	M_{min} $M_\odot$	M $M_\odot$	$\bar{n}$ cm^{-3}
a	$0.8^{+0.2}_{-0.6}$	1.7	$4.5^{+2}_{-0.5}$	2.3 10^{14}	15 10^{14}	260	5300	650
	$1^{+1}_{-0.5}$	1.9	3.8	0.7	17			
b	$1.4^{+2}_{-1.3}$	2.0	3.8	1.0	25	120	2800	650
c	–	2.0	–	0.7	–	150		100
d	$0.6^{+1.5}_{-0.5}$	1.7	3.9	0.7	9.2	150	2100	450
e	1.4^{+2}_{-1}	2.1	3.8	0.8	26	230	6500	650
f	$0^{+0.5}$	2.5	3.9	1.1			500	100

determined by dividing $I_i(=\int T_{A,i}dV)$ by $T_{A,i}$. The spread in ΔV within each region is a few times 0.1 km s^{-1}. Because in most of the regions the lines are weak, we could not derive the optical depth accurate enough for individual positions (this would result in a large overestimate of the mean column density), and only an estimate of the mean value of a whole region is given. Elsewhere (see Wouterloot and Habing, 1983), we have argued that there are good reasons to assume that line ratios smaller than 1.8 are optical depth rather than excitation effects. We also list column densities and masses, obtained if $\tau_3=0$ and $T_{ex}=5.5$ K is assumed, which results are listed in Table 4 as $N_{OH,min}$ and M_{min}.

Region *a* contains the most studied part of the cloud complex. The line ratio at the three positions of highest $T_{A,3}$ appeared to be higher than in the rest of this region. This points to a lower optical depth in the center of the cloud ($\tau_3 \simeq 0$) than outside the center ($\tau_3 \simeq 1$). There are two ways of explaining the situation.

a) The apparent high τ_3 outside the center is not real and caused by a positive DT.

b) The apparently low τ_3 in the center is not real and caused by a negative DT.

Considering the conditions in which such excitation effects can occur (Bujarrabal and Rieu, 1980) – velocity gradients through collapse or expansion, and the presence of an infrared radiation field, and also recent discoveries of a possible cluster of recently formed stars (Wilking and Lada, 1982) and of a large number of X-ray sources (Montmerle et al., 1983) possibly indicating the presence of many T Tauri stars in the center of the cloud, it is probable that explanation *b* is valid. This one (with $DT=-0.2$ K)

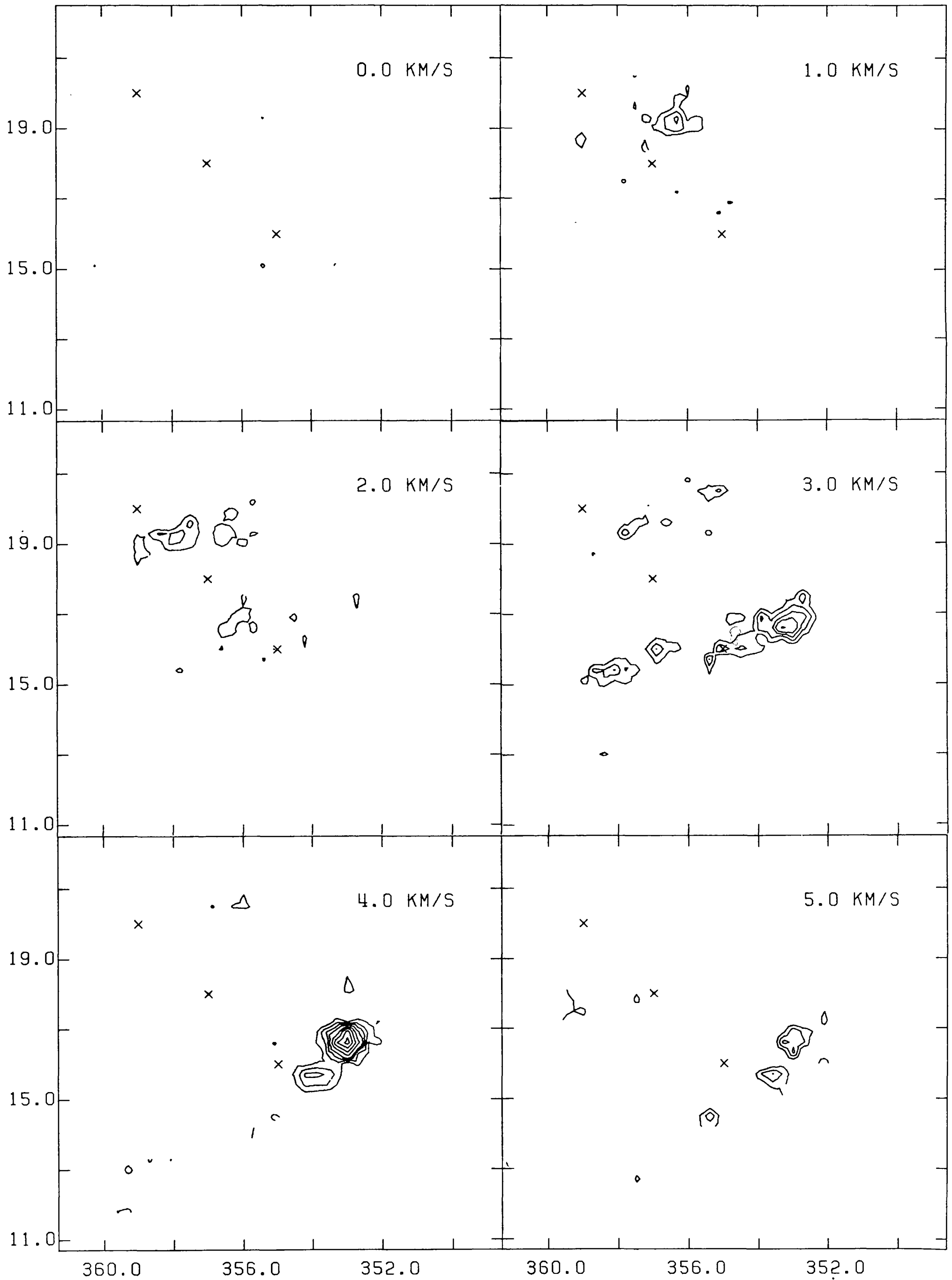

Fig. 4. Contour maps of $T_{A,3}$ at fixed velocities between 0 and $+5\,\mathrm{km\,s^{-1}}$. Contour values are the same as in Fig. 3

was adopted in the center. However it would be useful to measure the line ratio in the different parts of region a more accurately and with higher resolution.

Region *c* with streamer 2 has, apart from a 2° region east of region *b*, optically a very clumpy structure (see Barnard, 1927). The OH emission is only at a few scattered positions stronger than 0.04 K. This can only partly be due to the small width of the streamer (0°.6). If $\tau_3 = 0$, the mass is $150 M_\odot$, divided over 12 clouds between 5 and $45 M_\odot$. Region *d*, part of streamer 1, is in the OH maps much stronger than streamer 2. The observed linewidth is somewhat smaller than in other parts of the cloud complex. In region *e* the mean value of τ_3 is rather high and therefore also the mass, 60% of which is within Kh 556. We consider this value somewhat too high, especially if the extinction (on photographs) is compared with region a and region *d*. Region *f*, or Kh 569, shows a relatively large linewidth and a small optical depth. The mass is distributed over some smaller clouds of about $100 M_\odot$. There are a few small isolated low temperature clouds, especially L 1782 and 1796 between the regions *d* and *f* and near region *a*. Their total mass is less than $100 M_\odot$ if $\tau_3 = 0$; individual masses range from 7 to $20 M_\odot$.

A major problem in the interpretation is the filling factor *F*. On POSS prints the whole region is characterized by structures with widths of about 0°.5, the same as the size of the beam. If *F* is say 0.5, the lower limits are unaffected, but the upper limits of N_{OH} per beam area decrease with a factor 2. Because the abundances were derived in similar clouds but in some cases with smaller beam size for $F=1$, the effect on the mass is uncertain. The total mass of the Ophiuchus complex (region *a* to *e*) is $(1.2 \pm 1.0)\,10^4 M_{\odot}$. Since such uncertain corrections for $F<1$ have not been made in other complexes, we shall not do it in this case either. The central region and the streamers contain about an equal fraction of the mass (if the regions *b* to *e* are considered as streamers).

The mass of the Ophiuchus complex of $10^4 M_{\odot}$ is about the same as that of the Taurus complex, but an order of magnitude smaller than that of other giant molecular clouds. A difference with respect to other complexes seems to be the very fragmented nature. It is not at all certain that this difference is real. Because the streamers are very narrow, they would have been undetected at the distance of e.g. Mon OB 2.

In the different regions a mean density $\bar{n}$ was derived by dividing the total column density by the smallest dimension as seen on the sky. This $\bar{n}$ is not very accurate, due to the uncertainty in τ_3, but if it is adopted, the mean density within the whole complex is apparently larger (also if it is corrected for an $F<1$) than for other complexes at larger distance (Wouterloot, 1981) where it is about 100 cm^{-3} or lower. This can be an observational effect caused by unresolved structures within the more distant clouds.

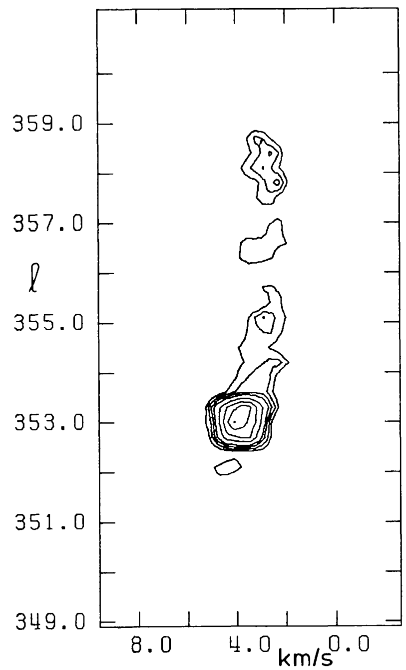

Fig. 5. Longitude-velocity diagram along streamer 1 at 1667 MHz. Contour values are the same as in Fig. 3

5. Velocity structure

Figure 4 shows the distribution of the emission at fixed velocities between 0 and $+5\,km\,s^{-1}$. The emission at the center of the ϱ Ophiuchi cloud is at $+4\,km\,s^{-1}$. Streamer 1 has a constant velocity of about $+3\,km\,s^{-1}$. Some emission from Kh 567 is at $+2\,km\,s^{-1}$ and the positions where streamer 2 is detected are at $+4$ or $+5\,km\,s^{-1}$. Kh 569 is visible at $+1$ to $+3\,km\,s^{-1}$.

Figure 5 shows an *l–V* diagram along streamer 1 through the center of the cloud.

The velocities of OH emission in region *a* agree with the H I results by Myers et al. (1978). Because the OH emission is detected at rather scattered positions it is difficult to determine a large-scale velocity pattern from these results. Therefore we have extended the H I data by using the Berkeley Survey (Heiles and Habing, 1974). The peak velocity of the H I was found by fitting a parabola through the parts of the profiles without self absorption. The H I emission was taken because the profiles do not show a dip over the whole area. Although due to the asymmetric profiles this procedure is not optimal, the resulting velocity is identical to the molecular velocity within the errors. The velocity field was smoothed to 0°.5 resolution and is shown in Fig. 6. It shows a gradient from $+4\,km\,s^{-1}$ near streamer 2 to $+1\,km\,s^{-1}$ between Kh 567 and Kh 569. At higher latitudes toward Kh 569 the H I and molecular velocities become higher again. Since the H I velocity is equal to the optical velocity (Beintema, 1975) and the molecular velocity (the present work, Myers et al., 1978), this gas is probably all at the distance of the cloud complex. The small velocity difference in Fig. 5 between $L=353°$ and the other parts is probably caused by the general velocity field of Fig. 6 and does not reflect streaming motion with respect to the center of the cloud.

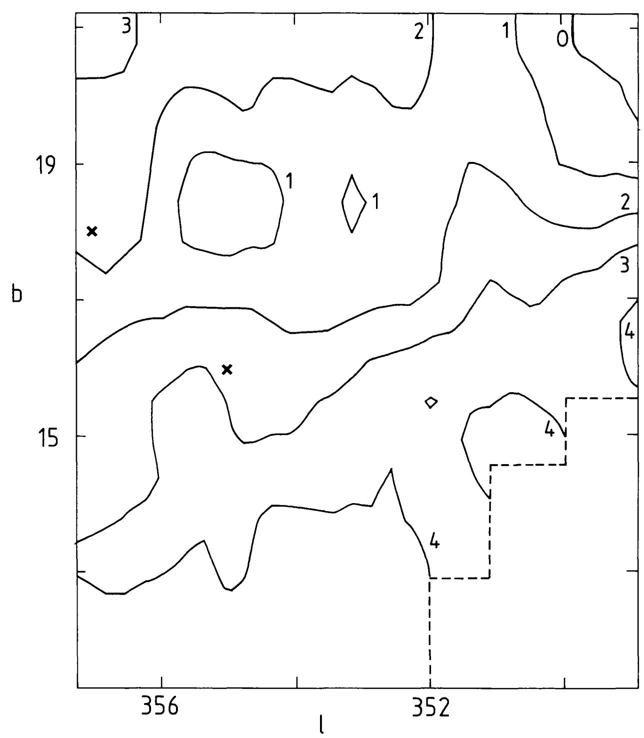

Fig. 6. The distribution of the H I peak velocity. The dashed line indicates the limit of the H I survey. The two crosses are at the same position as in Fig. 4. Contour values are 0, 1, 2, 3, and 4 $km\,s^{-1}$

6. Stars and star formation

The Ophiuchus molecular cloud complex is situated near the Sco OB 2 (or Upper Scorpius) association. This is a subgroup of the Sco-Cen association (Blaauw, 1964). It has a kinematical age of about $5\,10^6$ yr and a photometric age of about $(6 \pm 2)\,10^6$ yr. The mean radial velocity of the stars is $7\,km\,s^{-1}$ (with a dispersion of $8\,km\,s^{-1}$), to be compared with the velocity of the complex of about $3\,km\,s^{-1}$. In Fig. 7, the distribution of members of the association is shown. The members are divided into stars of type earlier and later than about B 3 (de Zeeuw, private communication). The streamers are directed away from the association. The mean position of the origin of the association as it was traced back from proper motions by Blaauw (1978) is around (350°.5, +22°.4). Blaauw mentions the possibility that there has been more than one center of star formation but the precise relation of these centers to the present outline of the clouds (age sequence) is not clear because the area which is covered by the association at the time of the closest approach is larger than the present area of the clouds. The average absolute radial velocity difference between other clouds and related associations is $5\pm4\,\mathrm{km\,s^{-1}}$ (Wouterloot, 1981). A similar tangential velocity can easily explain the present mean projected distance of 20 pc between the ϱ Oph cloud center and the position of formation of the association. The presence of a reflection nebula connected to Kh 569 and illuminated by ν Sco, a member of Upper Scorpius association, indicates that the distance of Kh 569 and the ϱ Oph clouds is practically the same. The total stellar mass of the Upper Scorpius association is about $2000 M_\odot$ (Blaauw, 1964). The ratio of the total molecular mass to stellar mass (OB stars) is thus about 8. This ratio (mass of giant molecular cloud (Blitz, 1978) to mass of the whole OB association (Blaauw, 1964)) in other regions is between about 1 (Cep OB 3) and 100 (Mon OB 1) and is typically 20. The result of the Ophiuchus complex, about 8 and even lower if one takes the total mass of the Scorpio-Centaurus association and a smaller F, is at the low side of the existing range. The different ratios are probably not caused by incompleteness of stellar data because there is no correlation of this ratio with distance. Because there is also no correlation with association age or the occurrence of subgroups within the associations, the original masses of the molecular complexes at the time at which star formation started must have been different. If the efficiency of the star formation process is about 10%, the Ophiuchus complex must have had originally a mass between $3\,10^4$ and $7\,10^4 M_\odot$. The upper value applies if the whole Scorpio-Centaurus association is included.

The process of star formation is still continuing, mainly in the front part of streamer 1. Wilking and Lada (1982) and Montmerle et al. (1983) discuss the presence of a cluster of young, low mass stars. However these processes are on a smaller scale than our OH observations, and we shall not make further comparisons. There are no signs of star formation in the other parts of the streamers or in Kh 569.

7. The structure of the Upper Scorpius region

Projected at the association is an H I emission feature with a velocity of $-12\,\mathrm{km\,s^{-1}}$ (Sancisi and Van Woerden, 1970). Interstellar absorption lines of Ca^+ seen in the spectra of some of the stars (Beintema, 1975), and with the same radial velocity,

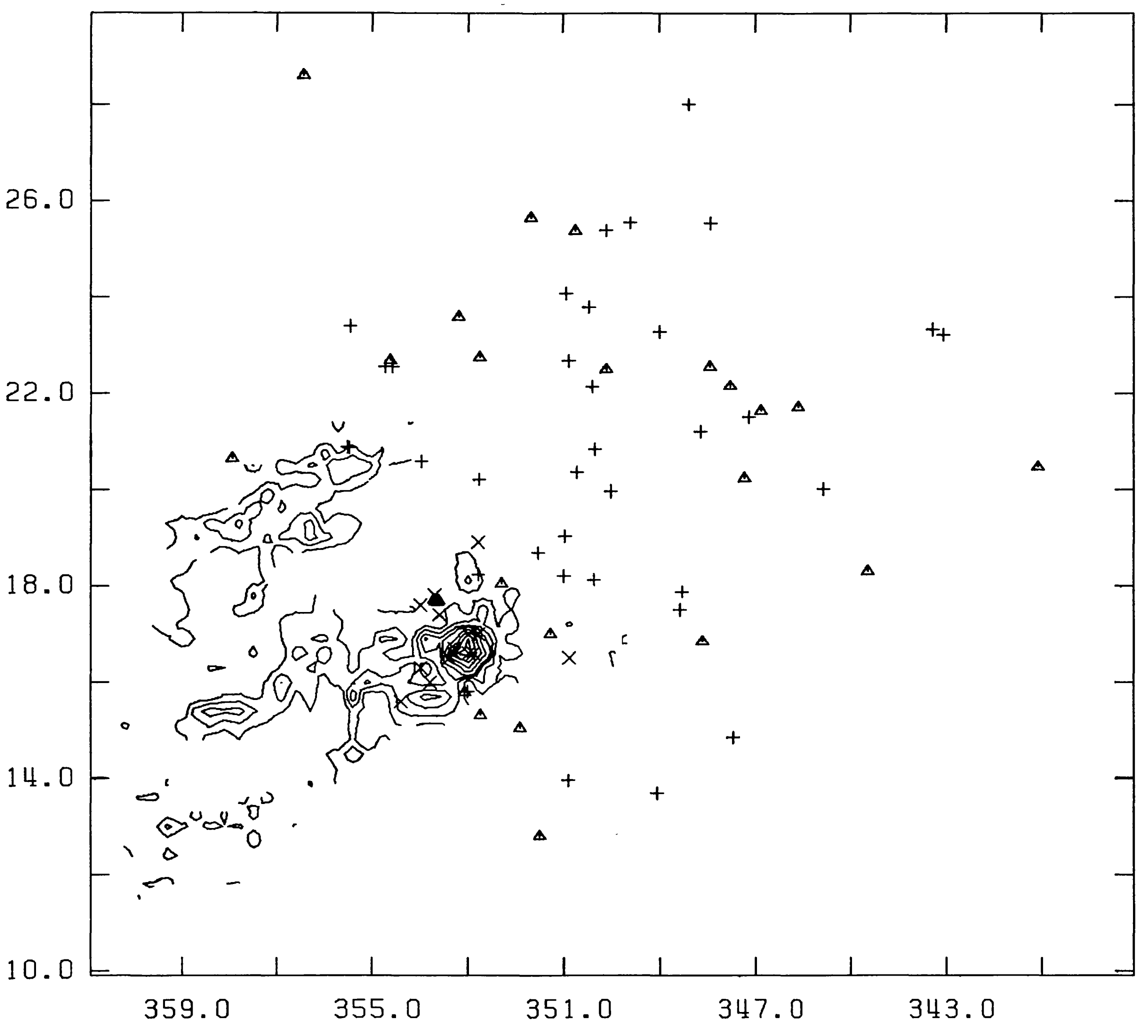

Fig. 7. The positions of bright (△) and fainter (+) members of the Upper Scorpius association and of T Tauri stars (×) with respect to the molecular clouds

indicate that the H I feature is situated between the stars and the Sun. The H I observations have been extended by Olano and Pöppel (1981). They detected a second maximum at (346°, +16°) beside the one at (352°, +22°). From the velocity structure they suggested the feature to be part of an expanding shell. Vidal-Madjar et al. (1978) argue that its distance is possibly very small (0.03 pc). If it is the frontside of an expanding shell, associated with the stars, the upper limit for the age is 10^7 years if the expansion velocity ($17\,\mathrm{km\,s^{-1}}$) is constant. If the radius of the shell is 20 to 40 pc, the age is 1 to 2 million years. This number is somewhat smaller than the age of the association, 5 to 6 10^6 yr, but of the same order as the kinematical age of ζ Oph, a star that started to run away from the association 1 10^6 yr ago (Blaauw, 1961).

The extended 2.3 GHz radio continuum emission mapped by Baart et al. (1980) in a region 8° in size coincides more or less with the center of the association and has a very sharp outer edge. It is partly anticorrelated with the molecular clouds and may be situated within the H I shell of Olano and Pöppel.

Because no velocity gradients are visible along the projected length of the streamers of about 18 pc, we are probably looking almost perpendicular to them. The morphology of the complex (consisting of a number of streamer-like features at different angular scales) and the position angle of these structures suggest that there is a relation between their formation and the association.

Two kinds of processes (possibly acting together) could have formed the structures through a kind of erosion of a parent cloud and the displacement of the material along magnetic field lines (see Vrba, 1977).

a) A slow process in which the eroding force is relatively low energetic, e.g. stellar winds of the members of the Upper Scorpius association. Timescales would be 5–10 10^6 yr and velocities 2–3 $\mathrm{km\,s^{-1}}$, using the ages of the Upper Scorpius and Scorpio-Centaurus associations, the length of the streamers and assuming that the process continued during the whole lifetime of the association.

b) A faster process caused by one (or more) supernova explosions in the area of the association. Loren and Wootten (1982) discuss the presence of a chocked region in the cloud center, with an elongation perpendicular to the direction of the streamers. Morfill et al. (1980) need the passing of shock through the cloud at the present time to enhance the γ-ray intensity and mention the presence of Loop I which however is relatively young and nearby, so it is not clear how the $-12\,\mathrm{km\,s^{-1}}$ feature is acting in this picture. Also it is not necessary that the streamers are formed through the same shock that at present triggers star formation. The similarity of the velocity field of streamers and of the large-scale H I may speak in favour of process *a*.

8. Conclusions

We have mapped 48 square degrees (or 425 pc^2) of the complex of molecular clouds near ϱ Oph in the two main lines of OH with a beam of 1.5 pc to determine the large-scale structure of the clouds in this area. This is the first extensive survey of these molecular clouds. The clouds are very fragmented and the total amount of mass in the area is about $(12\pm10)\,10^3 M_\odot$. Two separate cloud complexes appear to be involved, one with the ϱ Oph cloud as its main component, and the other associated with Kh 569. The mass of the ϱ Oph complex is probably nearly equally divided over the main region and the two streamers. The Kh 569 complex has a somewhat larger distance than the rest of the clouds and a mass of about $1000 M_\odot$. The mean densities of the clouds are in the order of $n_{\mathrm{H}_2}=400$ to $700\,\mathrm{cm}^{-3}$, however with a considerable uncertainty. Satellite line observations show that the main line excitation temperatures are equal except probably in the center of the ϱ Oph cloud. Along the streamers the radial velocity is constant but an overall velocity gradient is present perpendicular to the direction of the streamers. The molecular clouds have the same radial velocities as the background H I.

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