A CO survey of the dark clouds in Ophiuchus

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Abstract. CO observations covering 550 square degrees of the extensive complex of dark nebulae and molecular clouds in Ophiuchus are presented. The survey reveals a very filamentary system of clouds, five cloud complexes being identified in position and in velocity. The velocity dispersion of the whole region is 3.4 km s\(^{-1}\), which is typical for a molecular cloud complex. The total molecular mass of the region derived from the velocity-integrated CO intensity, combined with a \(W_{\text{CO}}\) to \(N(H_2)\) conversion factor based on gamma ray data, is \(10^4\) \(M_\odot\), while the virial mass of the molecular complex is an order of magnitude larger. Possible reasons for this discrepancy are discussed. The clouds are associated with the Upper-Scorpius subgroup of the Scorpio-Centaurus OB association. From the correspondence between velocities and column densities of optical absorption lines measured towards \(\zeta\) Oph and \(\gamma\) Oph, and those of the millimeter CO emission lines, upper limits to the distances of two cloud complexes are determined to be 140 and 150 pc respectively; one cloud complex is seen in optical absorption against the emission nebula surrounding \(\zeta\) Oph, which places an upper limit to its distance of 130 pc. From the size and the velocity dispersion the dynamical timescale for the cloud complexes is found to be \(\sim 10^6\) yr. The two filaments close to \(\gamma\) Oph are shown to have only a small velocity gradient, limited to the top part nearest \(\zeta\) Oph. The velocity and structural characteristics of these filaments suggest that a shock-formation model may be applicable.

Key words: interstellar medium: clouds: individual

1. Introduction

The well studied dark nebulae in Ophiuchus consist of a tangle of molecular clouds associated with the Scorpio-Centaurus OB association, the aggregate of early-type stars nearest to the Sun. The OB-association extends from \(l = 280^\circ\) to \(355^\circ\), between \(b = -10^\circ\) and \(+20^\circ\). The Ophiuchus clouds are situated from \(l \approx 345^\circ\) to \(10^\circ\), near the high-longitude edge of the association, and from \(b \approx 0^\circ\) to \(+25^\circ\). The optical appearance of this region as a whole is illustrated in Fig. 1, a copy of plate 5 from Ross and Calvert's (1934) Atlas of the Northern Milky Way.

Blaauw (1958) showed that the stellar Scorpio-Centaurus association consists of three subgroups, separated in position and in age. The youngest of these subgroups lies in Upper Scorpius, adjacent to the Ophiuchus clouds. The relationship between the early-type stars in this subgroup and the molecular clouds is obvious from the presence of reflection nebulae such as LBN 104 (associated with \(v\) Sco) and IC 4605 (22 Sco), and \(H\) regions such as Sharpless 1 (around \(\pi\) Sco) and Sharpless 9 (\(\sigma\) Sco). The distance to the stellar association is approximately 160 pc. The molecular clouds were shown to be at a distance of about 125 pc based on the visual extinctions of the stars as a function of distance (de Geus et al., 1988, hereafter Paper I).

This configuration of a young subgroup of an OB association located between a molecular cloud and older subgroups may be a consequence of sequential star formation (Blaauw, 1964; Elmegreen and Lada, 1977). The progression of massive star formation into a neighbourg molecular cloud due to already formed early-type stars is found also in other cases, such as in M17 (OB association Ser OB1), M42 (Orion), and W3. In the Ophiuchus molecular cloud region, a cluster of pre-main-sequence stars has been found as well, in the densest region next to \(\phi\) Ophiuchi (Grasdalen et al., 1973; Yrba et al., 1975; Elias, 1978). Wilking and Lada (1983) showed, however, that this cluster consists of low mass (1–3.5 \(M_\odot\)) pre-main-sequence objects, indicating that the sequence of massive star formation may have terminated with Upper Scorpius.

The goal of our investigation is to study the details of the interaction between the early-type stars and the interstellar medium in the Ophiuchus dense region. We attempt to explain the presence of a number of interesting features in the gas distribution; to establish the reason why massive star formation may have stopped with the birth of Upper Scorpius; to investigate the evolution of an OB-association subgroup relative to its parent molecular cloud; and to study the correlation of atomic and molecular gas and dust in the presence of a high ultraviolet (UV) radiation field. The proximity of the Upper-Scorpius/Ophiuchus region to the Sun provides a unique opportunity to study a number of aspects of the interaction of the newly-formed stars with the ambient medium in more detail than is possible for other regions.

The stars in the Sco-Cen OB association have been studied extensively: references are given in the review by Blaauw (1964) and in Paper I. Studies of the gas in the general region include the radio-continuum survey at 2.3-GHz by Baart et al. (1980), the \(H\) \(I\) studies by Sancisi and van Woerden (1970) and Cappa de Nicolau and Pöppel (1986), the OH survey by Wouterlood (1982), the CO work by Bronfman (1980), and the \(^{13}\)CO work by Loren (1989a, 1989b,

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1989b). The presence of an extended region of radio continuum emission related to Upper Scorpius was established from the 2.3-GHz survey. Sancisi and van Woerden (1970) discovered an H I feature in the direction of Scorpius moving at a velocity of \(-12\,\text{km}\,\text{s}^{-1}\) with respect to the local standard of rest, which is an anomalous velocity for a region so near zero longitude. Wouterloot derived optical depths, masses and velocities from OH data for a number of clouds in Ophiuchus. The regions mapped in the earlier OH and CO studies were limited to the sky within 10' north of the \(\varphi\) Oph dark cloud. On a much smaller scale radio observations of numerous molecules were made in the \(\varphi\) Oph dark cloud itself. (Encrenaz et al., 1975; Myers et al., 1978; Gottlieb et al., 1978; Loren et al., 1979, 1980; Lada and Wilking, 1980; Wootten et al., 1980a, b; Goldsmith and Linke, 1981; Loren and Wootten, 1986). A review of the central \(\varphi\) Oph region was given by Klose (1986). Absorption line studies of atoms and molecules towards the stars in the Upper-Scorpius association give very accurate measurements of the temperatures and column densities of the gas along the lines of sight (Hobbs, 1971; Willson, 1981; Chaffee and White, 1982; Jenkins et al., 1983; Danks et al., 1984; van Dishoeck and de Zeeuw, 1984; Meyers et al., 1985; Lambert and Danks, 1986). Comparison of the absorption line measurements to the large scale CO radio observations can reveal the location of stars with respect to the molecular gas. Because of the much better sensitivity of the absorption line studies, low-column density gas components may be observed, that are not found in the radio observations.

IRAS skyflux maps show that the dust in the Ophiuchus region extends well beyond the range of previous molecular surveys. In order to obtain a full picture of the distribution of the molecular gas in this part of the sky, a new survey was made of the area between \(l = 343^\circ\) and \(11^\circ\), and between \(b = 6^\circ\) and \(27^\circ\), in the \(j = 1 \rightarrow 0\) transition of \(^{13}\)CO. In Sect. 2 the details of the observations are described; in Sect. 3 the resulting maps are presented; in Sect. 4 a number of separate complexes are discussed, and in Sect. 5 possible models for the origin of the structures are discussed.

This article is the second in a series of papers in which the stars and the interstellar medium of Scorpio Centaurus are investigated. In Paper I the results of a photometric study of the early-type stars in Scorpio Centaurus were presented. In a future article (Paper III) the correlations between atomic and molecular gas and dust will be described. A model of the interaction of the stars with the interstellar medium will be the subject of a final paper (Paper IV).

2. Observations

The observations were made with the Columbia University Sky Survey Telescope at Cerro Tololo in Chile (Cohen, 1983), during August–September 1984 and October–November 1986. The telescope has a 1.2-m Cassegrain antenna with a beam of 8.8 ± 0.1 full-width at half-maximum at the CO \(j = 1 \rightarrow 0\) rest frequency of 115.2712 GHz. The spectrometer is a 256-channel filter bank with a frequency resolution of 100 kHz, corresponding to a velocity resolution of 0.26 km s\(^{-1}\). Velocities reported in this article are corrected for solar motion with respect to the Local Standard of
Rest, according to the convention that the Sun moves at 20 km s\(^{-1}\)
toward \(j = 56:160\) and \(b = 22:765\). The receiver was a liquid-
nitrogen cooled double-sideband Schottky-barrier diode mixer
with a receiver noise temperature typically less than 200 K. The
total system temperature is approximately 1000 K.

The instrumental zero level was determined by frequency
switching. The extremely narrow lines in the Ophiuchus region
allowed switching by only \(\Delta v = 4.0\) MHz (10.5 km s\(^{-1}\)). From the
resulting spectra polynomial baselines of first or second order
were subtracted. During the data reduction occasional bad
channels and the sharp telluric CO line were removed from
the spectra. The integration times were chosen such that an rms noise
temperature of 0.25 K was reached consistently. Standard cal-
ibration of the observations, with correction for atmospheric
attenuation was done with a room temperature black-body
chopper wheel. This yielded the temperature \(T'_{R}\) (Kutner and
Ulrich, 1981). In order to determine the radiation temperature \(T_R\)
(the physical temperature of a black-body that just uniformly fills
the main beam) \(T'_R\) was divided by the main beam efficiency, \(\eta\),
calculated by Bronfman et al. (1988) to have the value 0.82. In
order to put the temperatures on the same scale as the wide-
latitude survey of Dame and Thaddeus (1985), which was used e.g.
to derive the conversion factor of integrated \(^{12}\)CO intensity to \(H_2\)
column density (Bloemen et al., 1986), the values of \(T_R\) were
divided by 1.22. The resulting temperature scale is consistent with
that of previous work using the Columbia telescope (Ungeheuer
and Thaddeus, 1987; Dame et al., 1987; Nyman et al., 1987; de
Vries et al., 1987), but temperatures are probably about 20% below
the true radiation temperature (Bronfman et al., 1988).

Telescope pointing was accurate to within \(1'\), as was deter-
mined by observing stars through a small, collimated optical
telecope. Data were taken at full resolution but are under-
sampled, resulting in a final map with a grid of \(15'\) spacing. At the
distance of the Ophiuchus molecular clouds an angle of \(15'\)
corresponds to a linear size of 0.5 pc. A total of 5600 spectra were
obtained, covering some 450 square degrees. Figure 2 shows the
observed positions. The dashed line in the figure roughly outlines
the area covered.

Lines were considered real only if their peak intensity was
greater than 1.0 K and their velocity integrated intensity was greater
than 1.0 K km s\(^{-1}\). From the resulting dataset several separate
structures could be identified. At this point we are faced with the
problem of naming these structures in such a way as to typify their
properties. We will distinguish between complexes and clouds. In
this work clouds are the smallest units, identifiable in the survey
as positions of local maxima in the distribution of the CO
integrated antenna temperature: \(W(CO)\). Clouds are defined as
separate when the \(W(CO)\) values of the pixels connecting the local
maxima reach a value of less than 0.25 \(W_{\text{max}}(CO)\). Most of the
clouds, especially at galactic longitudes larger than 354°, tend to
occur in groups at the same velocity and at similar positions; these
we will call complexes. Five main complexes were found in the
Ophiuchus region, containing 32 clouds. A total of 14 clouds were
found, that are not obviously related to other clouds. The largest
clouds probably contain structure on a much smaller scale, but
any further substructure in our data simply failed to satisfy the
forementioned criterion. The clouds and complexes are defined in
Sect. 3, and described in Sect. 4. For each cloud identified, the
following parameters were calculated: maximum line tempera-
ture: \(T_R\); velocity at maximum \(T_R\); \(v\); integrated line intensity over
the whole cloud: \(W(CO) = \sum_{\text{spectra}} \int T_R \, dv\); mass of the molecular
material in the cloud: \(M(H_2)\) (the total gas mass, taking into
account the He-content of the cloud), is 1.4 times the molecular
mass); and full-width at half-maximum: FWHM. These
properties are listed in Table 1.

3. Results

Figure 3 shows the map of \(W(CO)\) over the entire relevant velocity
interval (\(-8\) km s\(^{-1}\) to 20 km s\(^{-1}\)). Because in most directions the
spectra are of simple shape, this map gives a good indication of the
distribution of the \(^{12}\)CO in the region. In a number of areas
overlapping clouds can be distinguished through inspection of their
velocity structure. We exhibit the velocity structure in two
ways: the first a set of channel maps integrated over a narrow
interval in velocity (2 km s\(^{-1}\)), the second a number of position-
velocity maps along separate clouds. Figure 4a–d shows the
channel maps of \(2\) km s\(^{-1}\) width, with the indicated range of
velocities.

The five main complexes, and the 46 clouds were distinguished in
Figure 4, separated both in space and in velocity. The positions of
the complexes and clouds are shown in Fig. 5. The galactic
coordinates of the clouds are listed in columns 2 and 3 of Table 1.
– Complex 1 is formed by the clouds seen in Fig. 4a around
\((l, b) = (3°, 22°)\).
– Complex 2 is seen most clearly in Fig. 4b and consists of the
clouds associated with L1752, \((l, b) \approx (35°, 3°, 16°)\), as well as with
the material in "Streamer 1" discussed by Vrba et al. (1975), at
\((l, b) \approx (35°, 16°)\).
– Complex 3 is formed by the material associated with
"Streamer 2" discussed by Vrba et al. (1975), it appears in Fig. 4c
around \((l, b) \approx (35°, 13°)\).
– Complex 4 also appears in Fig. 4c, around \((l, b) \approx (7°, 21°)\),
and is associated with L234.
– Complex 5 is formed by the clouds associated with L62,
\((l, b) \approx (16°, 16°)\), and is seen in Fig. 4d.

In Fig. 6 we show some of the prominent optical objects in the
area against the lowest contour of \(W(CO)\), including the dark
clouds from Lynd's (1962) catalogue, bright nebulae from
Lynd's (1965) catalogue, H\(\Pi\) regions from Sharpless's (1959)
catalogue, and the brightest stars from Upper Scorpius.

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### Table 1. Properties of CO Complexes and Clouds in Ophiuchus

<table>
<thead>
<tr>
<th>Cloud No.</th>
<th>b (°)</th>
<th>v_{LSR} (km/s)</th>
<th>FWHM CO (km/s)</th>
<th>W_{CO} (K km/s)</th>
<th>T_{R, max} (K)</th>
<th>R</th>
<th>M(H_2) (M_☉)</th>
<th>M_{VIR} (M_☉)</th>
<th>Complex</th>
<th>Associated Optical Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.25</td>
<td>24.50</td>
<td>0.76</td>
<td>11.58</td>
<td>3.8</td>
<td>8.9</td>
<td>0.55</td>
<td>1922</td>
<td>1 (E)</td>
<td>S27</td>
</tr>
<tr>
<td>2</td>
<td>-0.50</td>
<td>23.50</td>
<td>0.15</td>
<td>1.96</td>
<td>5.1</td>
<td>3.9</td>
<td>0.57</td>
<td>833</td>
<td>1 (E)</td>
<td>L145, Kh647, S27</td>
</tr>
<tr>
<td>3</td>
<td>4.00</td>
<td>22.75</td>
<td>-1.30</td>
<td>1.2</td>
<td>5.9</td>
<td>0.50</td>
<td>60</td>
<td>295</td>
<td>1 (E)</td>
<td>L156, Kh647, S27</td>
</tr>
<tr>
<td>4</td>
<td>4.25</td>
<td>22.00</td>
<td>-0.80</td>
<td>1.3</td>
<td>10</td>
<td>3.7</td>
<td>0.35</td>
<td>249</td>
<td>1 (E)</td>
<td>S27</td>
</tr>
<tr>
<td>5</td>
<td>2.75</td>
<td>22.00</td>
<td>0.32</td>
<td>1.7</td>
<td>5.5</td>
<td>0.25</td>
<td>62</td>
<td>674</td>
<td>1 (E)</td>
<td>L98, L105, L106, S27</td>
</tr>
<tr>
<td>6</td>
<td>3.75</td>
<td>21.00</td>
<td>-0.15</td>
<td>1.6</td>
<td>3.9</td>
<td>0.25</td>
<td>22</td>
<td>256</td>
<td>1 (E)</td>
<td>L121, S27</td>
</tr>
<tr>
<td>7</td>
<td>3.00</td>
<td>20.00</td>
<td>0.61</td>
<td>1.3</td>
<td>3.9</td>
<td>0.25</td>
<td>43</td>
<td>393</td>
<td>1 (E)</td>
<td>L143, Kh604</td>
</tr>
<tr>
<td>8</td>
<td>0.25</td>
<td>21.75</td>
<td>0.32</td>
<td>1.6</td>
<td>92</td>
<td>5.7</td>
<td>0.25</td>
<td>913</td>
<td>1 (T)</td>
<td>L1, Kh604</td>
</tr>
<tr>
<td>9</td>
<td>1.25</td>
<td>21.00</td>
<td>0.56</td>
<td>1.2</td>
<td>32</td>
<td>5.4</td>
<td>&lt;0.13</td>
<td>402</td>
<td>1 (T)</td>
<td>L43, Kh604</td>
</tr>
<tr>
<td>10</td>
<td>359.00</td>
<td>21.50</td>
<td>0.57</td>
<td>1.8</td>
<td>82</td>
<td>7.4</td>
<td>0.40</td>
<td>990</td>
<td>1 (T)</td>
<td>L1781, Kh604</td>
</tr>
<tr>
<td>11</td>
<td>355.50</td>
<td>20.75</td>
<td>3.10</td>
<td>0.8</td>
<td>220</td>
<td>10.3</td>
<td>0.30</td>
<td>247</td>
<td>405</td>
<td>L1719, Kh569</td>
</tr>
<tr>
<td>12</td>
<td>350.50</td>
<td>19.50</td>
<td>1.68</td>
<td>3.8</td>
<td>26</td>
<td>3.2</td>
<td>0.30</td>
<td>29</td>
<td>2471</td>
<td>L1770, Kh569</td>
</tr>
<tr>
<td>13</td>
<td>350.00</td>
<td>19.50</td>
<td>1.37</td>
<td>2.6</td>
<td>679</td>
<td>5.4</td>
<td>1.00</td>
<td>760</td>
<td>6980</td>
<td>L1752, Kh569</td>
</tr>
<tr>
<td>14</td>
<td>357.50</td>
<td>19.00</td>
<td>2.52</td>
<td>1.1</td>
<td>21</td>
<td>7.6</td>
<td>&lt;0.13</td>
<td>24</td>
<td>294</td>
<td>L1737, Kh569</td>
</tr>
<tr>
<td>15</td>
<td>358.50</td>
<td>17.50</td>
<td>2.29</td>
<td>2.3</td>
<td>78</td>
<td>5.5</td>
<td>0.35</td>
<td>87</td>
<td>1588</td>
<td>L1782, Kh569</td>
</tr>
<tr>
<td>16</td>
<td>355.75</td>
<td>17.25</td>
<td>2.18</td>
<td>1.4</td>
<td>931</td>
<td>8.7</td>
<td>1.00</td>
<td>2203</td>
<td>2206</td>
<td>L1709, L1739, L1740, L1744, L1755, L1765, Kh547, Kh556, Kh567, Kh568</td>
</tr>
</tbody>
</table>

**Notes:**

Column 4 gives the velocity with respect to the Local Standard of Rest ($v = 56°160$ and $b = 22°765$) at the peak of the integrated spectra of the clouds.

Column 6 lists the sum of the $W$(CO) of all spectra in the cloud.

Column 8 gives the estimated radius of each cloud in degrees. If a cloud is elongated, a short and a long dimension are given.

Column 9 $M$(H$_2$) was calculated from $W$(CO) using the conversion constant for $W$(CO) to $N$(H$_2$) from Bloemen et al. (1986), and assuming a distance to the Ophiuchus region of 125 pc (Paper I).

One of the most striking findings of the survey is that the CO distribution in Ophiuchus is very filamentary and clumpy. The 5 main complexes we have identified are all elongated, with an average length to width ratio of 8:1. The complexes definitely have the appearance of snake-like structures, intriguing in view of their location in the constellation of Ophiuchus, meaning the “snake bearer”. Complexes 1 and 4 are parallel, and make an angle of $-40°$ with the galactic plane. Complex 3, two clouds in complex 2, and the array of clouds in complex 5 are parallel to within $15°$. These complexes subtend an angle of $25°±10°$ with the galactic plane, and they appear to point past the q Oph dark cloud in the direction of the centre of the Upper-Scorpius OB association. The
direction of the magnetic field was measured by Yrba et al. (1976) for clouds 16, 17, and the $\phi$ Oph dark cloud, from the polarization of background stars. Over the whole length of both strongly elongated clouds 16 and 17, the field was found to be parallel to each cloud. In the central $\phi$ Oph region the magnetic field was shown to be bimodal (Wilking et al., 1979), with one component parallel to the fields in the elongated clouds, and one at an angle of 50°.

For each of the 46 clouds the integrated spectrum was determined. Of this spectrum the velocity at maximum temperature, the full-width at half-maximum and the total $W(\text{CO})$ were determined, and these are given in columns 4 to 6 of Table 1.
Column 7 lists the maximum radiation temperature in the object. Column 11 identifies the complex each cloud is associated with. In column 12 we list associated optical objects. This association is determined by the position and the shape of the optical objects as compared to the CO clouds, and is based on Fig. 6.

From the integrated CO intensity we can calculate the molecular mass of the clouds using an empirically established ratio of $W(\text{CO})$ to the H$_2$ column density. Although the CO line is usually optically thick, the fact that comparison with the more optically thin $^{13}$CO yields a fairly constant ratio of integrated intensities, and assuming that $^{13}$CO is a good molecular hydrogen mass tracer, indicates that $W(\text{CO})$ should be approximately proportional to the cloud mass. We adopt the ratio of $N(\text{H}_2)/W(\text{CO})$ which is based on a correlation analysis of CO, H I and γ-ray data over a large part of the sky (Bloemen et al., 1986):

$$\frac{N(\text{H}_2)}{W(\text{CO})} = 2.6 \times 10^{20} \text{ cm}^{-2} (\text{K kms}^{-1})^{-1}.$$

In order to determine the mass from the column density, the measured angular beamsize has to be converted to a linear size at the distance of the Ophiuchus molecular clouds. From a detailed photometric study of the early-type stars in the Scorpio-Centaurus OB association in Paper I, the distance to the Ophiuchus molecular cloud was shown to be 125 ± 25 pc. It will be assumed that this distance applies to all the objects identified in our survey. The masses derived on this assumption for our 46 clouds are listed in Table 1, column 9.

For comparison, the virial masses of the clouds that may have a roughly spherical shape, because their projected shape on the sky is more or less circular, were also determined. The virial formula for a homogeneous sphere was used together with the assumption of a Maxwellian velocity distribution. This covers mainly the smaller clouds. A word of caution is appropriate here: because of the undersampling of the survey, the radii for the smallest clouds ($< 0.35$) will generally overestimate the true radii. In those cases the virial mass estimates will be too high. For the larger elongated clouds, an estimate of the virial mass was made by assuming that they consist of $r_{\text{large}}/r_{\text{small}}$ separate clouds of radius $r_{\text{small}}$, where

$$r_{\text{small}}$$

is the radius perpendicular to the long direction of the cloud, and $r_{\text{large}}$ the radius in the long direction. In that case, velocity gradients over the filament were not included in the velocity dispersion. The underlying assumption is that if in fact the filament is virialized, it will be so along its short axis. The estimated sizes of the clouds are listed in column 8 of Table 1. The results for the virial mass are listed in column 9. In Sect. 5 a further discussion is given on the problems that confront different methods of mass determination of molecular clouds.

### 4. Description of complexes and clouds

Some of the properties of the main complexes and of a number of isolated clouds in the Ophiuchus region are discussed here in the context of a molecular cloud related to an OB association. Unless explicitly stated otherwise, all the masses quoted in the text are masses based on $W(\text{CO})$. In Paper III a detailed discussion will be presented of the relation of the molecular content of the Ophiuchus region with the atomic gas and the dust. For each complex we show position-velocity maps along the long dimension of the clouds. The loci along which these maps are drawn are shown in Fig. 7.

#### 4.1. Complex 1

Complex 1 can be seen most clearly in the first channel map (Fig. 4a). It consists of an elongated structure, complex 1 (E), extending from $(l, b) = (1.5, 21')$ to $(6.5, 25')$. At the lower latitude it connects with a T-shaped structure, complex 1 (T), situated perpendicular to the direction of elongation. In complex 1, 10 separate clouds were found. A number of these could be
identified with Lynds clouds. On a larger scale, the tip of the elongated structure (cloud 1) is related to Kh 647 (Khavtassii, 1960), and the T-shaped cloud with Kh 604. Figures 8a and b show the position-velocity maps along the elongated and the T-shaped cloud, respectively (see Fig. 7). The T-cloud (Fig. 8b) has a constant velocity of 0.46 km s$^{-1}$, and a total mass of 230 $M_\odot$. The position-velocity map along the elongated complex (Fig. 8a) shows a negative velocity gradient with increasing longitude of order $-0.6$ km s$^{-1}$/degree. There is also a hint of the presence of a second structure, parallel in the position-velocity map to the previous structure, some 2 km s$^{-1}$ higher. The total molecular mass of the whole elongated complex (both velocities) is 305 $M_\odot$; it subtends an angle of $-45^\circ$ with the galactic plane.

Complex 1 lies in the direction of the emission nebula surrounding the star $\zeta$ Oph, an O 9.5 main-sequence runaway star from the Scorpio-Centaurus OB association (Blauw, 1961), whose optical interstellar spectrum has probably been more intensively studied than that of any star. Emission from the elongated cloud drops to below the detection limit of our survey at the high longitude and latitude tip, just before it reaches the position of $\zeta$ Oph. In a recent article Langer et al. (1987) published a long integration CO spectrum towards $\zeta$ Oph. This showed three velocity components, including a strong narrow feature at $-0.8$ km s$^{-1}$, and broad features with peaks at $-0.1$ km s$^{-1}$ and 0.76 km s$^{-1}$. In Fig. 8a we have denoted the position of these peaks by crosses. From this figure it can be seen that Langer’s main line comes from the elongated cloud. The broad emission at the more positive velocities corresponds to cloud 2, or L145. All the CO seen in the direction of $\zeta$ Oph can therefore be associated with extended clouds. The same velocity structure is seen in the CO ($J = 2 \rightarrow 1$) line (Le Bourlot et al., 1989). Absorption line studies towards $\zeta$ Oph show a dominant molecular component at $v_{\text{LSR}} = -0.4$ km s$^{-1}$ (Morton, 1975), which may be identified with the elongated complex 1 (E). CH$^+$ is seen in absorption (Hobbs, 1973) at $v_{\text{LSR}} = 0.6$ km s$^{-1}$, which could be gas associated with cloud 2. The fact that the column densities derived from optical and millimeter data agree as well (Langer et al., 1987), implies that both cloud 2 and the elongated complex are in front of $\zeta$ Oph. This gives an upper limit to the distance of 140 pc. This conclusion is supported by the fact that both clouds are seen to absorb the visible light from the emission nebula surrounding $\zeta$ Oph, as can be seen in Fig. 13. Adopting a radius of 10 pc for the H II region (Draine, 1986) the upper limit to the distance of these clouds can be narrowed down further to 130 pc. The bottom of the T-shaped cloud is associated with Lynds 43, in which Herbst and Warner (1981) detected 2 TTauri stars. Our observations do not show any enhancements in the temperature or line width from these stars.

4.2. Complex 2

Complex 2 consists of three large and three small clouds. The three large clouds show some structure, but it is not enough to pass the criterion for cloud detection. Two of the large clouds (13 and 16) and two smaller clouds (12 and 15) show up in Fig. 4b. Clouds 11 and 14 have higher velocities, and are seen in Fig. 4c and d respectively. Clouds 13 and 16 are probably related: they are connected by cloud 15, and a further connection is evident from the lowest intensity levels. Both clouds 13 and 16 are inclined at an angle of 20$^\circ$ to the galactic plane. Wouterloot (1982) derived limits on the mass of a number of regions in Ophiuchus, on the basis of OH observations. Cloud 13 corresponds to his region $f$, for which he found a lower limit to the mass of 500 $M_\odot$. From our CO
observations a mass of 760 $M_\odot$ was derived. Cloud 16 is covered by Wouterloot's regions d and e, for which he found: $380 M_\odot \leq M_{16+e} \leq 8600 M_\odot$. The molecular mass, derived from $W(\text{CO})$ of cloud 16, is 1040 $M_\odot$. Loren (1989a) measured a $^{13}$CO-mass of 540 $M_\odot$. The three mass estimates are consistent.

The velocity structure along clouds 13 and 16 is shown in Fig. 9a and b. In Fig. 9b the central $\rho$ Oph region was included, which is seen as the broad peak at $v_{\text{LSR}} \approx 3$ km s$^{-1}$. The coincidence of this filament with the $\rho$ Oph region suggests a common origin. The velocity structure of cloud 16 is very smooth. From Fig. 9b it is clear that the Oph core and cloud 16 also overlap in velocity. Along the cloud a gradient in velocity was observed away from the central region. The lowest velocity (1.8 km s$^{-1}$) is reached 2.5 away from $\rho$ Oph. Further along the cloud the velocity turns back to more positive values. Cloud 16 is associated with the so-called “Streamer 1” (Vrba et al., 1976; Vrba, 1977), which will be discussed further in Section 5. The position velocity map along cloud 13 (Fig. 9a) shows a much more interesting structure. The different clouds 11, 13, and 14 are clearly separated in velocity. We therefore conclude that the two smaller clouds 11 and 14 are probably line-of-sight coincidences with the larger cloud 13. In Fig. 9a we included part of complex 5 (the bottom 13 pixels). From the velocities it appears that clouds 11 and 14 are related to complex 5. We will return to this matter in the discussion of complex 5.

The star $\chi$ Oph, $(l, b) = (357.9, 20.7)$, lies somewhat above cloud 13. The observation closest to the star shows no emission, but a single deeper integration on the star yielded a line with $T_R = 0.5$ K at 1.2 km s$^{-1}$, which corresponds well with the velocity of $C_2$ in optical absorption (van Dishoeck and de Zeeuw, 1984), the CH optical absorption line (Danks et al., 1984) and with a radio CH line (Wilson, 1981). We therefore conclude that the gas observed in absorption towards $\chi$ Oph is associated with cloud 13. The fact that this gas shows up in the optical spectrum indicates that the cloud either surrounds, or is located in front of the star. This suggests a distance of cloud 13 of approximately 150 pc. In the higher latitude end of the complex we find cloud 22, which is associated with a very small emission nebula (C 129), illuminated by three stars.

### 4.3. Complex 3

Complex 3 is a very long, narrow and straight filament that points away from the central $\rho$ Oph region in the direction opposite to that of the early-type stars. From the CO data separate clouds can be identified, starting with cloud 17 nearest to $\rho$ Oph. Cloud 17 is the most compact part of complex 3, with a column density of $3 \times 10^{22}$ cm$^{-2}$, and total mass of 800 $M_\odot$. Loren (1989a) gives a $^{13}$CO-mass of 790 $M_\odot$, which agrees exceptionally well with our estimate. Cloud 17 is associated with “Streamer 2” (see Sect. 5).
The top of this cloud, near α Oph, shows a sharp cutoff in intensity at $b = 16\degree 25$. Here the cloud borders on the bright nebula LBN 114, associated with the star 22 Sco. At lower latitude a gap exists between cloud 17 and the next in line, cloud 19. At $b = 10\degree$, cloud 19 connects with cloud 20, an X-shaped cloud. Comparison of the CO map with an optical picture of the structure, e.g. plate 3 of Ross and Calvert (1934), reveals two things: first of all that the complex becomes progressively patchier towards lower galactic latitudes (especially obvious in the optical), and second that the complex becomes wider in that same direction. It does however remain very straight: complex 3 lies to within $1\degree$ along the line $(l, b) = (3\degree, 8\degree)$ to $(353\degree, 16\degree)$, and it subtends an angle of $35\degree$ with the galactic plane.

At the high latitude part of the complex its width is $0.5\text{', or } 1\text{ pc}$ whereas at lower latitudes the width becomes $2\text{', or } 5\text{ pc}$. Figure 10 shows the position-velocity map along this complex. Starting at the α Oph dark cloud the velocity of complex 3 gradually increases when moving towards lower latitudes. Already before the gap, but definitely after it, the velocity turns back to the velocity of the α Oph cloud. If the gas in this complex is indeed gas moving away from the dense cloud, then this decrease in velocity might be explained as being a braking effect of the surrounding medium. At the low-latitude end of this complex the velocity structure becomes very interesting at the position of cloud 20. The velocity structure of the X-shaped cloud 20 is presented in Fig. 11a–f as channel maps integrated over $0.5\text{ km s}^{-1}$, from which it is clear that the two legs of the X are separated by $0.5\text{ km s}^{-1}$, and appear to twist around each other in velocity. Cloud 20 is the lower latitude continuation of cloud 19, which does not show a peculiar velocity behaviour. The optical picture shows the presence of very small structures that are absent in the CO survey. This absence is probably due to the undersampling of the CO.

4.4. Complex 4

Complex 4, consisting of 3 separate clouds, appears most clearly in Fig. 4c. Cloud 22 lies at the edge of the map, and has a mass of $270 M_\odot$. Cloud 21 is elongated parallel to the elongated cloud in complex 1; its mass is $560 M_\odot$. At the lower-latitude end of cloud 21 the third separate cloud 23 is located, which has a mass of $135 M_\odot$. Complex 4 as a whole subtends an angle of $-35\degree$ with the galactic plane. The position-velocity map along this complex (Fig. 12) shows a small gradient in velocity along the major axis. Again part of complex 5 was included in the position velocity map. The two complexes are seen to be at two different velocities. The apparent connection between the two is probably not real, but due instead to chance superposition. Complex 4 was studied in great detail by McCutcheon et al. (1986), who made $^{12}$CO and $^{13}$CO measurements, obtained optical polarization measurements of
Fig. 12. Position-velocity map along complex 4. The bridge between the clouds of complex 4 and those of complex 5 is very abrupt, and may be a line-of-sight effect. The numbers refer to the separate clouds in the complex.

Fig. 13. H$_2$ picture of the Ophiuchus molecular cloud region, from the survey by Sivan (1974). The large region to the upper left is the H II region S27 around the star ζ Oph. The shape of complex 4 is clearly traced in absorption against the lower left of the bright nebula. In the center of the nebula dust from two clouds (1 and 2) is seen to absorb the H$_2$ emission. From this observation the upper limit to the distance of these clouds can be established at 130 pc. The coordinates are accurate to within 0.2 only for the center of the picture. At the edges the distortions become very large, and the coordinates can no longer be trusted.

magnetic field in Complex 4, he obtained a value of 12 μG for the global-field pervading the molecular gas.

Complex 4 is seen projected on the emission nebulosity surrounding ζ Oph. Investigation of the H$_2$ picture by Sivan (1974), Fig. 13, shows the complex as a dark patch on the nebula. This suggests that the cloud is positioned in front of ζ Oph, either on the edge of the H II region, or well in front of it. This results in an upper limit for the distance of complex 4 of 130 pc. The lower part of complex 4 is associated with L162, a cloud containing 2 TTauri stars. Again no effect of their presence is seen in the CO lines.

4.5. Complex 5

Complex 5 is fairly well defined in Fig. 4d. It consists of seven separate clouds, strung out in $l$ at $b \approx 16.75$. The total molecular mass of these clouds is $\sim 550 M_\odot$. The angle between complex 5 and the galactic plane is approximately 15°. As mentioned previously, complex 5 may be associated with complexes 2 and 4. In Fig. 14 a full position velocity map is presented along complexes 4, 5, and 2 respectively. The jump in velocity between complex 5 and complex 4 suggests that their apparent connection is due to a chance superposition. In Fig. 14 a smooth connection can be seen between complex 5 and clouds 11 and 14 of complex 2, suggesting that these are one related structure. On the sky these clouds appear to be part of a ring, as was suggested by Herbst and Warner (1981). The direction of elongation of complex 5 however suggests a common origin with complexes 2 and 3, as discussed in Sect. 5.
4.6. q Ophiuchus region

The region around the star q Ophiuchi is a well-studied concentration of dark nebulae and molecular clouds, located at l = 352° to 354° and b = 16° to 19°. It is a region of ongoing star formation, according to Grasdalen et al. (1973), Vrba et al. (1975), Elias (1978), and Wilking and Lada (1983). The region forms the boundary between the bulk of the Ophiuchus molecular gas and the Upper-Scorpius stellar subgroup. The first CO map of this region was made by Encrenaz et al. (1975).

The total molecular mass of the cloud is 800 $M_\odot$. The position-velocity map of clouds 16 and 17 combined (Fig. 15) shows that the velocity of the q Oph cloud lies between the velocities of these two clouds. The integrated line of the whole area cannot be fit by a single Gaussian spectrum, but can be fit by two, one at 2.75 km s$^{-1}$ and one at 3.75 km s$^{-1}$. Lada and Wilking (1980) found self-absorbed lines at a velocity of 3.5 km s$^{-1}$ of both 12CO and 13CO, from which they concluded that part of the cloud is collapsing. From C$^{18}$O observations they determined the velocity of the densest part of the cloud to be 3.5 km s$^{-1}$. This velocity is consistent with the velocity of one of the fitted lines in our integrated spectrum. The second component may be gas associated with cloud 16. In Sect. 5 the origin of the elongated structures in the Ophiuchus region will be discussed in relation to the q Oph area. The highly reddened star HD 147889 is located in the dense cloud. C$_2$H absorption line observations by van Dishoeck and de Zeeuw (1984) revealed a component with $v_{\text{LSR}} = 2.7 \pm 0.5$ km s$^{-1}$ which can be identified with the low velocity component found in the integrated CO spectrum of the whole area. The CO column density obtained from the mm observations towards HD 147889 is much larger than that on the basis of the optical absorption line data, which implies that the star lies mostly in front of the cloud. CH absorption line observations of q Oph revealed a component at 2.9 km s$^{-1}$ which is also associated with the lower velocity CO gas.

4.7. Smaller clouds

A number of smaller clouds lie in the region of the young, early-type stars. Clouds 35 and 36 are associated with the reflection nebula IC 4592 around the star $\nu$ Sco, conforming closely to its high-longitude edge. Clouds 39, 40, 41, 42, and 43 appear to form the low-longitude edge of the emission nebula DG 141. The single cloud 34 may be associated with the reflection nebula adjacent to the star $\pi$ Sco. These isolated clouds are all associated with regions where interaction of the stars with the gas is evident. This suggests that we may be observing the remnants of a much more extensive system of molecular clouds, perhaps similar to that at higher longitude, which as been dissociated and dispersed by the intense ionizing radiation of the young stars. The presence of gas column densities below the detection limit of this survey can be revealed by absorption line studies towards the early-type stars. Through H I absorption line observations, Hobbs (1971) detected several components along lines of sight towards the Upper-Scorpius stars, of which the main component generally has a velocity between $-1.0$ and $+5.0$ km s$^{-1}$, which indicates gas associated with the Ophiuchus molecular cloud. Later absorption line observations of other atomic and molecular species (e.g. Willson, 1981; Chaffee and White, 1982; Jenkins et al., 1983; van Dishoeck and de Zeeuw, 1984; Danks et al., 1984; Meyers et al., 1985) also showed that molecular gas at similar velocities to that of the Ophiuchus molecular clouds is present, albeit at low column densities, outside the boundaries of the radio detected molecular cloud.

5. Origin of the cloud structures

The large scale filamentary nature of the Ophiuchus region, apparent in the dark nebulae, is equally or even more conspicuous in the distribution of the associated molecular clouds. The occurrence of filaments in molecular clouds is quite common. Elongated structures similar to the ones observed in Ophiuchus are found for example in the Taurus clouds (Ungerechts and Thaddeus, 1987) and in Orion (Maddalena et al., 1986; Bally et al., 1987). Two mechanisms for the formation of these structures have been proposed. The first is fragmentation of isothermal sheet-like clouds. Miyama et al. (1987) showed from numerical calculations that sheets tend to form filaments due to the growth of perturbations. Their calculations also showed that the filaments will refract to form clumps. This model requires the presence of sheet-like structures, which may be provided by supernovae or wind-blown bubbles. The time-scales on which such filaments condense are unknown, but these will depend strongly on initial conditions in the sheet. A second model for forming filaments involves a plane shock wave propagating past a dense cloud, producing a conical wake (bow shock), which can deposit mass in an elongated structure behind the cloud (Rozyczka and Tenorio-Tagle, 1985). Such a formation process is suggested for cometary globules.

The different filaments in the Ophiuchus molecular cloud region may be examples of both formation processes. Two groups of elongated structures can be identified from the CO survey, with properties that are suggestive of their origin. Complexes 1 and 4 are inclined by $-40^\circ$ with the galactic plane and with the projected line connecting them with the centre of the stellar OB association in Upper Scorpius. Furthermore, they do not appear to be related to a particularly dense cloud. The two complexes are situated projected on a large H I structure, component P in the paper by Cappa de Nicolau and Pöppel (1986). These facts may indicate formation in a sheet, the H I cloud being the sheet-like structure in which the complexes condensed. For Complex 4 McCutcheon et al. (1986) and Heiles (1988) already
suggested, based on the mass-dependence of the velocity profile and the magnetic field being perpendicular to the long axis of the cloud, that it formed in a sheet of atomic gas. Heiles (1988) proposes that it is part of the H I-shell associated with the North Polar Spur, but de Geus (1989) shows that it is more likely to be associated with a smaller expanding shell around the Upper Scorpius OB association. It is unlikely that the shock-formation model is applicable here, because of the absence of dense cores at the tip of the structures, and because of the large angle between the elongation of the complexes and the direction towards the stars, which are the most likely source of shocks in this region.

The two clouds 13 and 16 of complex 2, the elongated complex 3, and the string of clouds of complex 5, all subtend angles of $25^\circ \pm 10^\circ$ with the galactic plane, and so point in the direction of the OB association in Upper Scorpius. Furthermore both cloud 16 and complex 3 are clearly associated with the dense $\phi$ Oph cloud. The other structures have no obvious association with a dense molecular cloud, but they are associated with a small H I cloud, around $(l, b) = (354^\circ, 20^\circ)$. Both the $\phi$ Oph molecular cloud and the H I cloud lie between the elongated structures and the O and B stars, suggesting that the shock-formation model may apply to these clouds. The origin of the shock lies most likely in the OB association, but whether it is caused by stellar winds or by one or more supernovae cannot be deduced from the CO observations. The energetics of the region will be discussed in Paper IV. Vrba et al. (1976) and Vrba (1977) already proposed a similar model for clouds 16 and 17. A velocity difference between the two filaments and the core, reported by Vrba (1977) was interpreted as evidence for a streaming motion, hence the designation “Streamers”. From the length of the clouds and the velocity difference, an age of approximately $6 \times 10^4$ yr was derived for both filaments. The coincidence of this age with the nuclear age of the Upper Scorpius OB subgroup led Vrba to suggest a common origin for the stars and the filaments. The interpretation of clouds 16 and 17 as streaming away from the central dense region is supported by our observations. In Figure 15 a velocity gradient, albeit small, over these two clouds away from the core is clearly seen. The velocity difference rises until $\approx 3^\circ$ away from $\phi$ Oph. Further along both clouds the velocity difference decreases again, possibly owing to braking by the surrounding gas.

A number of points of Vrba’s interpretation need to be revised on the basis of more recent studies, including the present one. His age estimate, based on the length and the velocity of the shock-induced filaments, should be reconsidered, because the velocity of the central dense core was found to be different (Wilking and Lada, 1983) from the value he used, and because cloud 17 was found to be part of a much longer structure (complex 3) extending all the way to the galactic plane. A better age estimate of the shock-induced filaments requires a more detailed knowledge of the shocks interacting with the dense cloud. Some further constraints can be put on the formation process of the elongated structures discussed here, from a comparison with the Orion A molecular cloud. The Orion A molecular cloud has a length of $\approx 35$ pc, similar to complex 3, and was suggested by Bally et al. (1987) to be the result of the propagation of a shock front into a dense molecular cloud, similar to the formation model for complex 3 (Vrba, 1977). The Orion A cloud is much more massive than complex 3, but, more importantly, it shows a velocity gradient out to its very tip of $\sim 1$ km s$^{-1}$ per degree. In complex 3 a velocity gradient is only seen close to the $\phi$ Oph complex itself, but at lower latitudes the velocity is equal to the velocity of the dense central region. If indeed the formation process of complex 3 is similar to that of Orion A, albeit on a less “massive” and energetic level, the lack of a velocity gradient along the complex can be explained by a projection effect: the filament should be close to the plane of the sky. How close depends of course on the true velocity away from the core, but assuming a velocity difference of 3 km s$^{-1}$ between the top and the bottom, the angle with the plane of the sky has to be less than 10$^\circ$ for it to remain undetected in this survey. Although this angle is small it cannot be ruled out.

In Paper IV a model for the large scale structure of the Ophiuchus molecular cloud will be presented, in which the different formation models will be discussed further.

5.1. Cloud stability

In Sects. 3 and 4 the virial masses of the clouds in the Ophiuchus region were estimated. A comparison of these with the masses based on $W$(CO) show a large difference. The mean ratio $M_{VIR}/M_{CO}$ is $10$. This might indicate that the Ophiuchus molecular clouds are generally unbound, but their filamentary, knotted structure suggests just the contrary. The question arises, does this difference between the mass estimates tell us anything about the dynamics of a clump or a cloud? A number of problems immediately arise:

The conversion factor from $W$(CO) to $N$(H$_2$) is based on a correlation study of H I, CO, and $\gamma$-rays of a large sample of clouds of different physical properties. The application of such a global parameter to a specific cloud may not yield the correct value for the mass of that cloud. The Ophiuchus region is known to have enhanced temperatures, due to the presence of the early-type stars. However, as was shown by van Dishoeck and Black (1988), the conversion factor is inversely proportional to the temperature, so that our mass estimates based on $W$(CO) would come out even lower.

The velocity structure of the cloud may not be governed only by its gravitational potential. As was suggested by Keto and Myers (1986), and shown by Maloney (1988), the external pressure term in the virial equilibrium equation is non-negligible. Neglecting the external pressure when estimating the virial mass will cause the latter mass estimate to be too large. The same effect occurs when magnetic fields are important in the cloud, as was shown by Myers (1987).

Even if the virial theorem as used here would be valid, the use of the approximation of a homogeneous sphere in the determination of the virial masses may be inaccurate, because the radial density structure of each cloud is doubtless more complex.

It is thus possible that the difference between the virial mass and that derived from the CO luminosity does not necessarily imply that the clouds are gravitationally unbound. A similar calculation for the whole Ophiuchus region is also of interest. The radius of the ensemble of clouds was taken to be $10^2$ to $10^5$, and its full-width at half-maximum was found to be $3.4$ km s$^{-1}$. The resulting virial mass then is between 5 and $7 \times 10^5 M_\odot$. The total mass deduced from $W$(CO) was found to be $9 \times 10^3 M_\odot$. For the region as a whole, therefore, we also find a significant difference between the two mass estimates. This discrepancy is most likely due to ignoring the effects of external pressure and magnetic fields in the calculation of the virial mass.

On the basis of the size $L$ and the velocity dispersion $\sigma$, the dynamical timescale $\tau$ of the clouds can be determined: $\tau = L/\sigma$ (Larson, 1981). The average dynamical timescale for each cloud is of the order of $10^5$ yr. The physical interpretation of this timescale depends on the dynamical state of the cloud. In virial equilibrium, for instance, the equilibrium condition will be valid over timescales $\gg \tau$. In the absence of equilibrium, $\tau$ gives the timescale on
6. Conclusions

An area of approximately 450 square degrees in the Ophiuchus molecular cloud complex was mapped in the $J = 1 \rightarrow 0$ line of $^{12}$CO. The survey shows that the clouds are very filamentary with lengths up to 25 pc and widths as little as 2 pc. Most filaments in addition have clumps or knots on scales of approximately 1 to 2 pc. Five different cloud complexes separated in position and velocity were identified and catalogued. For complexes 1 and 2 upper limits to the distances were derived from a comparison of the CO velocities and column densities with velocities and column densities from absorption line measurements towards $\zeta$ Oph and $\chi$ Oph: 140 pc, and 153 pc, respectively. For complex 4 an upper limit to the distance of 130 pc was derived from the fact that the cloud is seen in absorption against the H II region S27 around $\zeta$ Oph.

The mass of the separate clouds identified in the survey was derived from the integrated CO intensity, using the conversion factor of $W$(CO) to $N$(H$_2$) as derived by Bloemen et al. (1986). The total mass of the region was found to be $9 \times 10^4 M_\odot$. The estimates of the virial mass, assuming homogeneous spherical clouds, were generally an order of magnitude higher. This discrepancy is most likely due to neglecting the effects of external pressure and magnetic fields on the stability of the clouds. Inclusion of these terms would lower the virial mass estimate.

The elongated complexes 2 and 3, and the string of clouds of complex 5, all point in the direction of the Upper-Scorpius OB association. Furthermore complex 3 and cloud 16 of complex 2 are obviously related to the dense $\rho$ Oph molecular cloud, and complex 5 and cloud 13 of complex 2 are associated with a dense H I cloud. These observations support a formation model that involves the passage of a shock, caused by the Upper-Scorpius stars, through a dense gas cloud. The filamentary complexes 1 and 4 do not point in the direction of the stars in Upper Scorpius. They are related to a large H I structure, and do not show dense concentrations at their tip. Complexes 1 and 4 are therefore plausibly formed by condensation in sheets of gas.

A velocity gradient away from the $\rho$ Oph dense cloud was observed, supporting the idea of “streaming” gas-filaments (Vrba, 1977). However the gradient is small, and not constant, reversing sign at a distance form the dense core. In a future paper (de Geus, 1989, Paper IV) a model will be presented for the Ophiuchus molecular cloud complex, in which the formation of the system of molecular clouds will be considered in the context of the available H I and infrared data.

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