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# Infrared polarimetry of dark clouds – II. Magnetic field structure in the $\rho$ Ophiuchi dark cloud

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**Summary.** We have obtained *K*-band polarimetry of 20 sources embedded within the densest region of the $\varrho$ Oph dark cloud. The degree of polarization ranges from 1.1 to 7.4 per cent, and the position angles have a bimodal distribution, centred at 50° and 150°. The 50° component, which permeates the surrounding region, persists in the region of the dense $C^{18}O$ ridge, and is perpendicular to the elongation (NW–SE). The flattened shape of the condensation could be due to the effect of a magnetic field with matter contracting preferentially along the field lines. If the magnetic field is enhanced by at least one order of magnitude, over the interstellar value, the cloud collapse could be retarded in the direction transverse to the magnetic field. The sources forming the 150° component are located around the densest region between the $\varrho$ Oph B1 and B2 clouds. This component, which is nearly perpendicular to the ambient field, could be caused by rotation of $\varrho$ Oph B with a rotation axis parallel to the existing magnetic field.

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## 1 Introduction

Recent infrared and radio observations suggest that dark clouds are sites of low-mass star formation. Determination of the temperature, density, velocity, and magnetic field structure of these clouds are crucial in developing an understanding of the conditions for star formation. It has long been recognized that magnetic fields significantly affect the physical structure, dynamical state and evolution of dark clouds, but a major difficulty in fully understanding the role of magnetic fields is the lack of sensitive observational probes.

Optical polarization has been used to map the structure of the magnetic field in the galaxy. However, very little polarization work has been done in dense cloud regions, because the apparent magnitudes of the background stars are very faint due to heavy extinction. For the central region of star formation the extinction is so large, typically $A_V \sim 10$ mag, that the polarimetric work must be performed in the infrared; the extinction at 2.2 $\mu$m, $A_K$, is only one tenth of the visual extinction, $A_V$. Here, we employ infrared polarization measurements to describe the cloud morphology in the nearby dark cloud complex, $\varrho$ Oph. We have previously presented results on the Taurus Dark Cloud (Tamura *et al.* 1987, Paper I).

Near-infrared surveys of the $\varrho$ Oph region have been carried out by Grasdalen, Strom & Strom (1973), Vrba *et al.* (1975), Elias (1978) and Wilking & Lada (1983, hereafter WL). The recent work of WL has resulted in the detection of 20 infrared sources in an area once thought to be devoid of such objects. From analysis of the near-infrared and mid-infrared energy spectral distributions, WL suggest that the infrared cluster is predominantly composed of low-luminosity stars which may still be contracting toward the main sequence. Observations of $C^{18}O$ reveal a centrally condensed ridge of gas extending in the NW–SE direction and containing extremely large column densities of gas and dust (i.e., $50 \lesssim A_V \lesssim 100$ mag). An unusual region of 2-cm $H_2CO$ emission, named $\varrho$ Oph B, has been found at the NE edge of the central $C^{18}O$ cloud by Loren *et al.* (1980). High-resolution $H_2CO$ (Martin-Pintado *et al.* 1983; Wadiak *et al.* 1985) and $NH_3$ (Zeng, Batrla & Wilson 1984) maps of $\varrho$ Oph B show elongations in the same direction as the central $C^{18}O$ ridge. Recent maps of $DCO^+$ and $HCO^+$ (Loren & Wootten 1986) of the $\varrho$ Oph region, have revealed a remarkable morphology in $\varrho$ Oph B region; the $\varrho$ Oph B was spatially resolved into three components, B1, B2 and B3. As derived by Loren & Wootten (1986), $\varrho$ Oph B1 is an elongated cloud with a position angle of 150°, defined by $NH_3$ and 2-cm $H_2CO$ emission lines. $\varrho$ Oph B2 lies directly to the north-east and is elongated at an angle of 50° as defined by $DCO^+$ and $H^{13}CO^+$ emission lines. Many far-infrared observations for the $\varrho$ Oph cloud exist with the observations of Cudlip *et al.* (1984), Wilking *et al.* (1985), and Young, Lada & Wilking (1986) covering the region of interest here.

## 2 Observations and results

The *K*-band (2.2 $\mu$m) polarization measurements were performed with the Kyoto Polarimeter on the 3.8-m United Kingdom Infrared Telescope (UKIRT), Mauna Kea, Hawaii in May and July 1985. We employed a beam of either 12 or 19 arcsec with a chopping throw of 30 arcsec in an east–west direction at a frequency of 3.5 Hz. The polarimeter consists of a rotating half-wave plate and a fixed wire-grid analyser. The half-wave plate with an aperture of 50 mm is located centrally in the $f/35$ beam, just above the dichroic mirror. The rotation speed of the half-wave plate is 32 s per rotation. The wire-grid analyser is mounted over the window of the cryostat (UKT9). We sample one data point every 1 s and eight data points per sinusoidal wave.

The instrumental polarization was measured to be $0.08 \pm 0.11$ per cent by observing the unpolarized star, $\beta$ Com. The efficiency of the polarimeter was measured by observing the same star, $\beta$ Com, with an additional wire-grid polarizer of known efficiency fixed over the half-wave plate. The position angles were calibrated by observing the known polarized source, GL 2591 ($\theta_k = 171°$: Lonsdale *et al.* 1980).

*K*-band polarizations were measured for all the 20 sources detected in the survey of WL, and four additional sources, GS26, VS5, VS18 and EL28.

The results are presented in Table 1. The *K*-band magnitudes derived from the *I*-component of the Stokes parameters are presented in the fifth column of Table 1. Uncertainties in the photometry are estimated to be 0.15 mag. The magnitude of WL12 shows a significant difference from that of WL (1983),* indicating that this star may once have undergone an FU Orionis-type brightening at infrared regions. The polarization vectors, superposed on the total extinction map of WL, are presented in Fig. 1. Our values are shown as circles with thick lines and previous data as squares with thin lines (Vrba, Strom & Strom 1976; Wilking *et al.* 1979); the length of the plotted vector is proportional to the magnitude of polarization.

**Table 1.** Observational results. First column is a list of objects measured in the present work. Second, third and fourth columns represent degrees ($P_K$), uncertainties ($\sigma_p$), and position angles ($\theta$) of polarization. Fifth column is $K(2.2\,\mu m)$-band magnitudes derived from the *I*-component of Stokes parameters. Sixth column is the date of the observations.

| Object | $P_K$ (%) | $\sigma P$ (%) | $\theta$ (°) | K-mag | Date (1985) |
|---|---|---|---|---|---|
| WL 1 | 3.51 | 0.54 | 157 | 10.58 | May 20 |
| WL 2 | 3.29 | 0.61 | 35 | 10.78 | May 20 |
| WL 3 | 2.17 | 0.68 | 126 | 11.07 | May 20 |
| WL 4 | 2.13 | 0.17 | 177 | 9.17 | May 20 |
| WL 5 | 5.88 | 0.44 | 153 | 10.12 | May 20 |
| WL 6 | 5.05 | 0.66 | 130 | 10.06 | May 20 |
| WL 7 | 1.40 | 0.50 | 170 | 11.04 | Jul 24 |
| WL 8 | 5.60 | 0.60 | 168 | 9.46 | May 20 |
| WL 9 | 3.82 | 1.07 | 28 | 11.80 | Jul 24 |
| WL10 | 3.07 | 0.41 | 55 | 8.78 | May 20 |
| WL12 | 4.90 | 0.23 | 50 | 8.99 | May 20 |
| WL13 | 1.54 | 0.20 | 93 | 9.19 | May 20 |
| WL14 | 2.16 | 0.94 | 54 | 11.69 | Jul 24 |
| WL15 | 6.52 | 0.07 | 22 | 7.04 | Jul 24 |
| WL16 | 4.87 | 0.23 | 27 | 7.81 | May 20 |
| WL17 | 4.99 | 0.41 | 42 | 10.14 | May 20 |
| WL18 | 1.14 | 0.26 | 45 | 9.85 | May 20 |
| WL19 | 7.41 | 0.67 | 46 | 10.89 | May 20 |
| WL20 | 5.21 | 0.35 | 56 | 9.11 | May 20 |
| GS26 | 4.09 | 1.07 | 176 | 9.49 | May 20 |
| | 4.04 | 0.14 | 171 | 9.34 | Jul 24 |
| | 4.37 | 0.21 | 174 | ---- | Jul 25 |
| VS 5 | 3.13 | 0.20 | 19 | 9.99 | Jul 24 |
| VS18 | 0.68 | 0.15 | 164 | 9.49 | Jul 24 |
| EL28 | 0.73 | 0.06 | 29 | 6.73 | Jul 24 |

## 3 Discussion

We first make some general statements about possible mechanisms for producing polarization towards dark clouds. Polarization studies of embedded infrared sources suggest that the polarization can be produced (i) by transmission of radiation through a medium of aligned grains with the position angle of polarization tracing the projection of the magnetic field lines on to the sky, or (ii) by scattering of radiation from an asymmetric distribution of grains around the stars. Recent

*Subsequent photometry on the same night and on July 6 and 7 with the UH 2.24-m telescope showed the brightening of this source to be as large as 2.78 mag at *H*, 1.91 mag at *K* and 1.0 mag at *L*, compared with the photometry of WL.

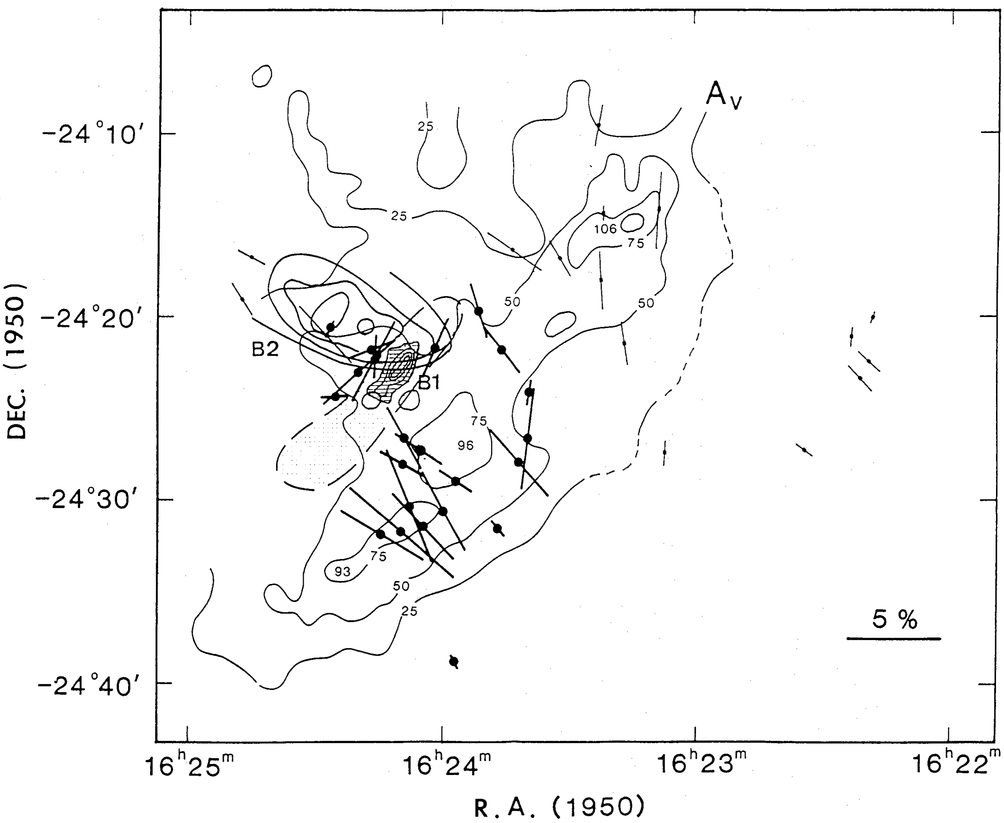


**Figure 1.** *K*-band polarization of the central core region of the ϱ Oph dark cloud. Polarization vectors are superimposed on the map of the visual extinction derived from $C^{18}O$ data. Contours of $A_V$ are marked in increments of 25 mag with the peak values given for the three largest enhancements. Present data are shown by circles with thick lines. Those of Wilking *et al.* (1979) in this area are shown by squares with thin lines. The boundaries of $H_2CO$ (Martin-Pintado *et al.* 1983) and $HCO^+$ (Loren & Wootten 1986) of ϱ Oph B1 cloud are presented by a parallel and a dotted pattern, respectively. The density of ϱ Oph B2 from $DCO^+$ (Loren & Wootten 1986) is shown by heavy solid contours.

infrared polarization and molecular spectroscopy studies suggest the many embedded sources, obscured by circumstellar discs, have associated reflection nebulosities and molecular outflows which lie perpendicular to the plane of the disc. Radiation emerging along the poles of the disc, and scattered into the line-of-sight has a position angle of polarization parallel to the disc. Discs or other condensations, which form by cloud collapse occurring preferentially along magnetic field lines, will be elongated in a direction perpendicular to the field lines. Hence, the scattered radiation referred to above, will be polarized with a position angle perpendicular to the ambient magnetic field lines of the cloud.

### 3.1 DIRECTION OF POLARIZATION VECTORS

The distribution of position angles in the optical (Vrba *et al.* 1976) is shown in Fig. 2(a) and in the *K*-band (Vrba *et al.* 1976; Wilking *et al.* 1979 and the present data) in Fig. 2(b)–(d). There is a clear concentration of position angles around 50°.

A bimodal distribution of position angles centred around 0° and 50° was noted by Vrba *et al.* (1976) from optical polarimetry and by Wilking *et al.* (1979) from infrared polarimetry. The concentration of position angles around 50° that we observe in the central dense $C^{18}O$ region is

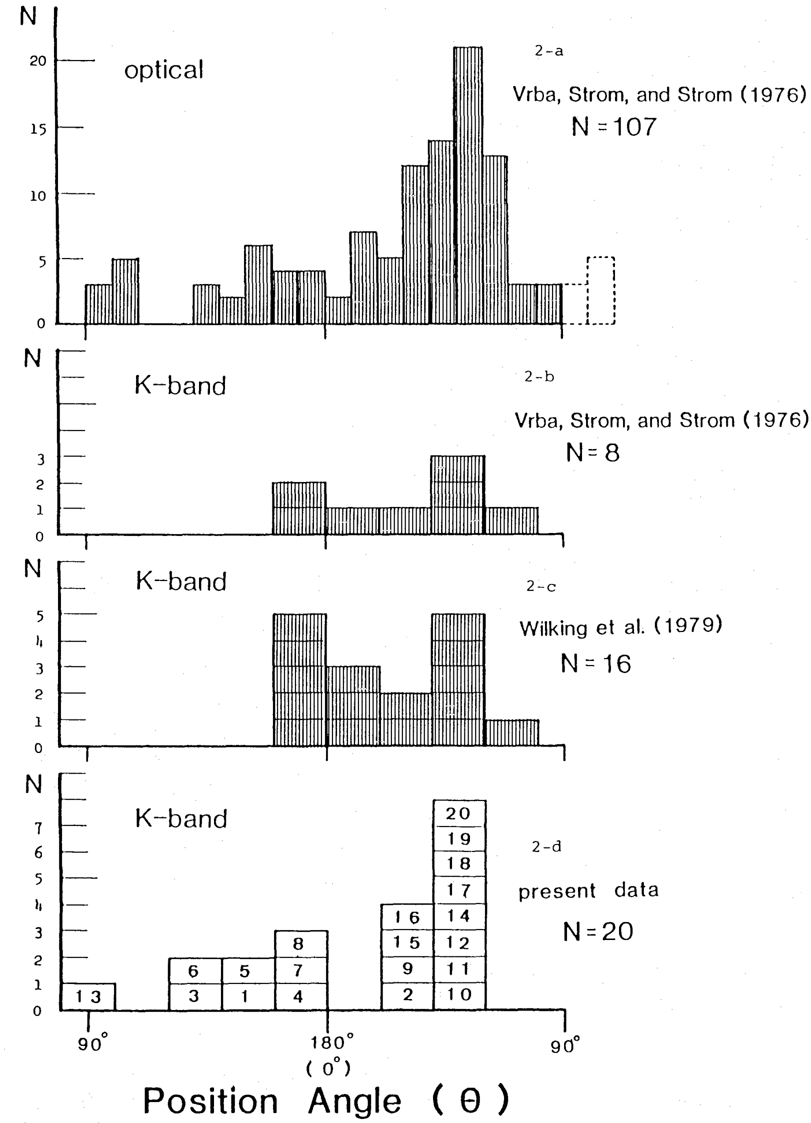


**Figure 2.** Histograms of the distribution of optical (a) and *K*-band (b, c, d) polarization angles. Notice that the areas sampled in (a), (b), (c) and (d) are different.

well correlated with the 50° component previously obtained both in the optical and the *K*-band over the majority of the cloud (Figs 1 and 2b and c).

Seven sources have position angles spread between 90° and 180°. Two of these, WL7 (170°) and WL8 (168°) would appear to belong to the previously identified 0° component. The other 5 sources are confined to the region around the dense molecular cloud, $\varrho$ Oph B and form a distinct component of position angles of ~150°, not previously observed. Combining the present data with previous observations, we conclude that there are three components of position angles centred around 0°, 50° and 150°.

*(i) The 50° component*

Twelve (60 per cent) of the 20 sources form a narrow distribution of position angles for infrared polarization between 20° and 60° (Fig. 2d). The optical polarization vectors in the periphery of the dark cloud show a similar distribution of position angles. Our results therefore show that this component persists within the densest region of the $\varrho$ Oph dark cloud. The majority of the observed sources exhibit infrared excess in the mid-infrared region (Lada & Wilking 1984), which might arise from thermal radiation from a dust shell and/or free–free emission from a gaseous envelope surrounding the star. Although any scattering of radiation from an asymmetric distribution of scatterers around the star would produce intrinsic polarization, the extent of the 50° component throughout the cloud extending over several degrees indicates that the polarization must be caused predominantly by the passage of radiation through aligned grains in the dark cloud. We shall refer to the 50° component as the direction of the general magnetic field in the cloud, as was previously suggested by Vrba, Strom & Strom (1976) and Wilking *et al.* (1979).

The most striking feature of previous optical polarization measurements is the alignment of position angles with the two long streamers of dark clouds extending to the north-east from the central ridge. In the central region, however, the position angles of infrared polarization are orthogonal to the ridge of $C^{18}O$ emission (Fig. 1). This seems to contradict the tendency for a number of elongated dark clouds to be aligned parallel to the interstellar magnetic field (Heiles 1973). But this relationship is derived from the observations of H I, dark cloud surveys on Palomar Sky Survey plates, and optical polarimetry, and so refers only to tenuous interstellar clouds with $n_{\rm H\,I} \lesssim 10^3\,{\rm cm}^{-3}$ and $A_V \lesssim 10$ mag. In the densest portion of the $\varrho$ Oph dark cloud, the polarization vectors show the opposite tendency. That is, they are perpendicular to the orientation of flatness.

*(ii) The 0° component*

The sources (WL7 and 8) are located in the western part of the $C^{18}O$ ridge, and probably belong to the neighbouring 0° component region described by Wilking *et al.* (1979). This component was interpreted as arising from a separate cloud overlying the general magnetic field direction of 50°. The boundary of this component extends to the east and the south of $\varrho$ Oph A, but does not appear to permeate the south-eastern part of the $C^{18}O$ ridge ($\varrho$ Oph B and C regions). This is consistent with the velocity discontinuity seen near the boundary by Scalo (1984) from $C^{18}O$ data.

*(iii) The 150° component*

The sources WL1, 3, 4, 5 and 6 have polarization position angles which are almost perpendicular to the 50° component. These sources (probably together with VS18) are confined to an area between $\varrho$ Oph B1 and B2 (Loren & Wootten 1986) and coincide with the mid-infrared enhancement (no. 12) of the *IRAS* survey (Young *et al.* 1986). They also lie close to the S0 (Gottlieb *et al.* 1978), $H_2CO$ (Loren, Sandqvist & Wootten 1983; Martin-Pintado *et al.* 1983; Wadiak *et al.* 1985) and $NH_3$ (Zeng *et al.* 1984) emission regions. The dense core of $\varrho$ Oph B1 shows a disc-like shape with density of $\gtrsim 10^6\,{\rm cm}^{-3}$ (Loren *et al.* 1983; Loren & Wootten 1986), and has a clumpy structure with a velocity gradient (Wadiak *et al.* 1985).

We will discuss the possible causes of the 150° polarization. The first and simplest possibility is that an additional cloud is overlying the general (50°) cloud. However, there is no support for this argument from either infrared or molecular data.

Secondly, as described at the start of Section 3, some pre-main-sequence stars have a tendency to be polarized perpendicularly to the general magnetic field. For example, T-Tauri stars in the Taurus Dark Clouds, and infrared sources associated with molecular outflows are polarized at a position angle nearly perpendicular to those of nearby field stars (Moneti *et al.* 1984; Hodapp 1984; Sato *et al.* 1985). The four sources, WL3, 4, 5 and 6 are thought to be either T-Tauri stars or protostars from their mid- and far-infrared luminosities (Lada & Wilking 1984; Young *et al.* 1986), and $\varrho$ Oph 1 (VS26 = WL3/4/5) does show a $^{12}CO$ emission line with a width of

$\Delta V \sim 10\,\mathrm{km\,s^{-1}}$, although it has not yet been spatially resolved (Bally & Lada 1983). Hence, polarizations perpendicular to the ambient magnetic field might be expected for these four sources.

Finally, if the magnetic field is frozen into the cloud material, and if the field is not much stronger than the equipartition strength during collapse, the field could be twisted around by 90° by rotation of the cloud. This would be consistent with the proposed 'spindle' rotation of the B2 cloud core about a rotation axis parallel to the ambient magnetic field (Loren & Wootten 1986). Such cloud rotation is also thought likely to result in the formation of a disc elongated in a direction perpendicular to the direction of the ambient magnetic field. $\varrho$ Oph B1 does indeed show a disc-like shape, elongated in the direction NW–SE (Fig. 1) (Martin-Pintado *et al.* 1983; Zeng *et al.* 1984). Alternatively, Loren & Wootten argue that the flatness of the $\varrho$ Oph B1 cloud is due to a compression front propagating through the region from the SW side.

At a density of $10^5$ or $10^6\,\mathrm{cm^{-3}}$, for this region of the cloud, collisions between gas molecules and dust grains would disorder the grain alignment by keeping $T_d$ close to $T_g$. Naïve application of the usual Davis–Greenstein theory by substituting the parameters of gas density and temperature into the formula given by Jones & Spitzer (1967) leads to extremely strong magnetic fields, on the order of milligauss (Dyck & Beichman 1974). Nevertheless, we believe that the Davis–Greenstein theory (1951) is probably incomplete, and that grain alignment can occur in such a dense cloud.

### 3.2 CLOUD EVOLUTION OF THE CENTRAL $C^{18}O$ REGION

We begin by estimating the various energies associated with the central $C^{18}O$ region of the $\varrho$ Oph cloud. Although the central ridge is elongated, with a projected area of $20\times40$ arcmin (corresponding to $1\times2$ pc, WL), we will assume for simplicity a spherical geometry of radius 1.5 pc. Taking a mass $\sim 550\,M_\odot$ (WL), $\Delta V = 1.7\,\mathrm{km\,s^{-1}}$ and $T_g \sim 15$ K (Mizuno & Fukui 1986, private communication), we calculate a gravitational energy of $1.0\times10^{46}$ erg and a thermal energy of $3.4\times10^{45}$ erg, somewhat less than the gravitational or the kinetic energy. The magnetic field energy, $B^2R^3/6 \sim 1.7\times10^{43}\,B^2(\mu\mathrm{G})$ erg, would be comparable if the magnetic field is enhanced by an order of magnitude (i.e. $\sim 30\,\mu$G), compared to the diffuse interstellar medium. If this is so, the cloud would become centrally contracted in a direction along the magnetic lines of force, resulting in a flattened condensation elongated perpendicular to the magnetic fields (see Fig. 1). The mass of the central concentration of $\varrho$ Oph, estimated to be $\sim 550\,M_\odot$ (WL), is in agreement with the theoretical value of $M_c \sim 740\,M_\odot$ at which the gravitational term exceeds the magnetic term for pre-collapse values of $n$ and $B$ equal to $20\,\mathrm{cm^{-3}}$ and $2.5\,\mu$G, respectively, typical for a diffuse cloud (Spitzer 1978).

The magnetic field throughout the $\varrho$ Oph dark cloud is perpendicular to the central ridge of $C^{18}O$ (see Section 3.1), and is well aligned parallel to the line of force of the large-scale magnetic field delineated by the optical polarization sky survey of Mathewson (1968). We suggest, therefore, that the $\varrho$ Oph $C^{18}O$ ridge has indeed formed by contraction along the magnetic tube, resulting in an oblate self-gravitating cloud with its major axis normal to the field lines. Because of non-homogeneous contraction, and flattening occurring preferentially parallel to the lines of force, the magnetic field should increase less rapidly than for the case of a three-dimensional 'frozen-in' field (i.e. $\propto n_g^{2/3}$) (Mouschovias 1976). This would produce fields consistent with the upper limits of $50\,\mu$G measured by Crutcher *et al.* (1975).

A similar configuration, with the cloud elongation orthogonal to the cloud polarization, is also seen for Heiles Cloud 2 in the Taurus Dark Cloud (Moneti *et al.* 1984; Tamura *et al.* 1986). From $^{13}CO$ observations the size and mass of the Heiles Cloud 2 is estimated to be $2\times4$ pc and $700\,M_\odot$, respectively (Schloerb & Snell 1984). Schloerb & Snell argued that the structure of Heiles Cloud 2 has been produced by the collapse and fragmentation of a rotating cloud with an initial diameter of 20 pc. On the other hand, the well aligned polarizations, perpendicular to the flatness of the cloud, led Moneti *et al.* and Tamura *et al.* to infer that the structure of Heiles Cloud 2 might be determined by the magnetic fields.

Virial (gravitational, kinetic and thermal) energy estimates for the $\varrho$ Oph B1 cloud are of order $10^{44}$ erg, assuming a size $\sim 0.15 \times 0.03$ pc, mass $\sim 18\,M_\odot$, $T_k \sim 20$ K and $\Delta V \sim 1$ km s$^{-1}$ (Loren & Wootten 1986). Unless the magnetic field is enhanced by two orders of magnitude (up to 200 $\mu$G), it has less influence upon the gas motion and structure. This is different from the situation for the central $C^{18}O$ ridge as described earlier. We, therefore, favour rotation of the $\varrho$ Oph B2 condensation, as suggested by Loren & Wootten, as the explanation of the 150° component.

## 4 Conclusions

We present new infrared polarization measurements of infrared sources embedded within the centrally condensed core of the $\varrho$ Oph cloud. All 20 sources show substantial levels of polarization and the position angles show a bimodal distribution at 50° and 150°.

(i) The infrared polarization of the 50° component in the central region of the $\varrho$ Oph dark cloud is well correlated with the optical polarization in the outer region.

(ii) The average position angle of the 50° component is perpendicular to the elongation of the $C^{18}O$ ridge and the $\varrho$ Oph B1 cloud.

(iii) The strength of the magnetic field could retard contraction of the cloud in the direction perpendicular to the magnetic field and preferential contraction along the magnetic field lines would form the flattened central $C^{18}O$ ridge.

(iv) The newly discovered 150° component might originate through the twisting of the magnetic fields by rotation of the $\varrho$ Oph B clouds.

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