Evolution of Magnetic fields in Bok globules?

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Abstract. We study the influence and structure of the magnetic field in the early phases of low-mass star formation using polarization maps of Bok globules at a wavelength of 850 $\mu$m, obtained with the Submillimeter Common-User Bolometer Array (SCUBA) at the James Clerk Maxwell Telescope (JCMT). We discuss observations of the following sources: CB 26 - a small globule with a nearly dispersed dense core and a young and large circumstellar disk, CB 54 - a large globule with a massive dense core and a deeply embedded young stellar cluster, and B 335, CB 230, and CB 244 - three nearby, relatively isolated small globules with low-mass protostellar cores.

We find strongly aligned polarization vectors in the case of CB 26, B 335, and CB 230, while the vector orientations in the case of CB 54 and CB 244 are more or less randomly distributed. The degree of polarization, amounting to several percent, was found to decrease toward the center in each source. Assuming dichroic emission by aligned non-spherical grains as the polarization mechanism, where the magnetic field plays a role in the alignment process, we derive magnetic field strengths and structures from the observed polarization patterns.

We compare the magnetic field topology with the morphology and outflow directions of the globules. In the Class 0 sources B 335, CB 230, and CB 244, the magnetic field is oriented almost perpendicular to the outflow direction. In contrast, the inclination between outflow axis and magnetic field direction is much more moderate ($36^\circ$) in the more evolved Class I source CB 26.

Keywords: Magnetic fields — Polarization — Individual objects: CB 26, CB 54, CB 230, CB 244, B 335 — Magnetic fields — Submillimeter

1. Introduction

Bok globules are small, relatively isolated, simply-structured molecular clouds and therefore excellent objects to study the earliest processes of star formation, in particular the interplay between protostellar collapse, fragmentation, and magnetic fields. Signs of star formation in many Bok globules include bipolar molecular outflows (e.g., Yun & Clemens 1994a), infrared colors, and sub-millimeter properties that are consistent with Class 0 protostars or embedded Class I sources (Yun & Clemens 1994b, Launhardt & Henning 1997).

To study one of the key parameters of the star formation process – namely the magnetic field – submillimeter polarization measurements represent a powerful technique. Assuming emission by aligned nonspherical grains as the
dominating polarization mechanism, where the magnetic field plays a role in the alignment process, magnetic field strengths and structures can be derived from the submillimeter polarization pattern (e.g. Wolf et al. 2003, Henning et al. 2001).

2. Observations and Data reduction

We observed the Bok globules CB 26, CB 54, B 335, CB230, and CB 244 for which brief descriptions are given in the following: **CB 26** is a small, slightly cometary-shaped Bok globule at $D = 140$ pc. The globule contains a nearly dispersed dense core and a young and large, perhaps early protoplanetary disk (Launhardt & Sargent 2001). **CB 54** is a large Bok globule associated with the molecular cloud BBW 4 at $D = 1.1$ kpc (Brand & Blitz 1993) and the reflection nebula LBN 1042. The globule contains a massive dense core of $M_H = 100 M_{\odot}$, which is associated with a bipolar molecular outflow (Launhardt & Henning 1997; Yun & Clemens 1994a). At near-infrared wavelengths, a small, deeply embedded young stellar cluster becomes visible. **B 335** is an isolated, nearly spherical Bok globule at a distance of 250 pc (Tomita et al. 1979, Frerking et al. 1987). The deeply embedded Class 0 protostar drives a collimated bipolar outflow with a dynamical age of $3 \times 10^4$ yr (e.g. Chandler et al. 1990, Chandler & Sargent 1993). **CB230** is a small, bright-rimmed Bok globule in a distance of 400 pc associated with the Cepheus Flare molecular cloud complex. The globule contains a protostellar double core with a separation (east-west). The western source with the more massive accretion disk and envelope drives a large-scale collimated molecular outflow of dynamical age $2 \times 10^4$ yr (Yun & Clemens 1994a). The eastern source drives a weaker outflow that is probably not aligned with the large-scale outflow (Launhardt et al., in prep.). **CB 244** is an isolated Bok globule located at a distance of 180 pc and probably associated with the Lindblad ring (Kun 1998). It contains two dense cores separated by $90^\circ$. The more prominent south-eastern core is associated with a bipolar molecular outflow with a dynamical age of $10^4$ yr (Yun & Clemens 1994a; Launhardt et al. 1997).

The observations were performed at the 15-m James Clerk Maxwell Telescope (JCMT) between March 1 and 6, 2000 and between September 10 and 14, 2001. The effective beam size (HPBW) is $14.7''$ at $850\mu$m. Polarimetry was conducted with the Submillimeter Common-User Bolometer Array (SCUBA; Holland et al. 1999) and its polarimeter, SCU-POL, using the 350-850 $\mu$m achromatic half-waveplate. Flat-fielding, extinction correction, sky-noise and instrumental polarization removal have been performed with the data reduction package SURF (Jenness & Lightfoot 1998). The polariza-
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Figure 1. **Left:** SCUBA intensity map (850 µm) of the Bok globule CB 26 with overlaid iso-intensity contour lines (contour levels: 0.15%, 0.30%, ..., 0.90% of the maximum intensity) and polarization pattern. Furthermore, the mean direction of the polarization \( \vec{\gamma} \) \( (\sigma_\gamma) \) is shown. **Right:** Central part of the Bok globule CB 26 (from Launhardt & Sargent 2001). \( J - H \) color map of the bipolar near-infrared reflection nebula (black contour lines: \( K \) band emission). The white contour lines show the proto-planetary disk discovered by Launhardt & Sargent (2001; contour levels: 4, 11, ..., 32 mJy arcsec \(^{-2}\); obtained with OVRO at 1.3 mm - beam width: 0.58" - 0.39"). (from Wolf et al. 2003)

The polarization was computed using the POLPACK data reduction package (Berry & Gledhill 1999).

We restrict the polarization analysis to the regions in which the total flux density per beam is above 5 times the rms in the maps (measured outside the central sources). We do not use polarization vectors derived at positions where the scatter of the total flux density measurements between the jiggle cycles was larger than 20% of the average total flux density at that point and exclude polarization vectors with \( P_l = \sigma(P_l) < 3 \), where \( \sigma(P_l) \) is the standard deviation of the polarization degree. The resulting polarization maps are shown in Fig. 1 and 2.

### 3. Polarization versus Intensity

As found in previous polarization measurements towards other star-forming cores (see, e.g., Matthews & Wilson 2002, Houde et al. 2002, Glenn et al. 1999), the degree of polarization decreases towards regions of increasing intensity (see Fig. 3). Possible explanations for this behavior are: (a) increased densities in the cores, which cause an increase of the collisional disalignment rate of the grains towards the centers of the cores, (b) insufficient resolution of the field structure associated with the core collapse, and (c) spherical grain
Figure 2. SCUBA intensity maps (850 µm) with overlayed iso-intensity contour lines (contour levels: 0.15%, 0.30%, ... 0.90% of the maximum intensity) and polarization patterns of the Bok globules CB 244, CB 54, B 335, and CB 230. Furthermore, the solid/dashed contour lines represent the spatially well-separated blue-shifted/red-shifted outflow lobe seen in either the $^{12}$CO(1-0) or $^{13}$CO(1-0) spectral channel maps of CB 244 (blue/red-shifted outflow contour lines begin with 0.5 K km s$^{-1}$/0.6 K km s$^{-1}$ and are stepped by 0.15 K km s$^{-1}$/0.2 K km s$^{-1}$; from Yun & Clemens 1994a), CB 54 (blue/red-shifted outflow contour lines begin with 1.7 K km s$^{-1}$/0.45 K km s$^{-1}$ and are stepped by 0.3 K km s$^{-1}$/0.15 K km s$^{-1}$; from Yun & Clemens 1994a), B 335 (contours are spaced at 2σ intervals of 200 mJy beam$^{-1}$; from Chandler & Sargent 1993), and CB 230 (blue lobe: $v_{\text{LSR}} = 1.6 \pm 0.2$ km s$^{-1}$ - solid contours, red lobe: $v_{\text{LSR}} = 3.0 \pm 0.2$ km s$^{-1}$ - dashed contours. The step width amounts to 0.3 km s$^{-1}$ for both lobes; from Launhardt 2001) are overlayed. (from Wolf et al. 2003)

growth in the denser regions which would result in unpolarized re-emission by the dust (Weintraub et al. 2000). Because of the large density contrast between the unresolved central condensations and the envelopes, the increasingly poor grain alignment as density increases is expected to be the main effect.
Figure 3. Scatter diagram showing the distribution of the linear polarization degree $P_l$ vs. intensity $I$ across the Bok globules. Additionally, data obtained for the Bok globule CG 30 have been taken into account. The solid line represents the best fit of the function of the form $P_l = a_0 + a_1 \left( \frac{I}{I_{\text{max}}} \right)^{a_2}$, where $P_l$ is the degree of linear polarization, $I$ is the measured intensity, and $a_0$, $a_1$, and $a_2$ are constant quantities.

Furthermore, the observations of B 335 and CB 230 not only show a decrease of the polarization degree, but also that the orientation of the polarization vectors does not change remarkably towards the dense cores. This supports the hypothesis that despite the decrease of the grain alignment rate, the magnetic field structure in the cores of these objects is not seriously disturbed, and thus still represents the primordial field. In the case of CB 244 and CB 54 on the other hand, the orientation of the polarization vectors and therefore the structure of the magnetic field in the cores is irregular and we assume that it can no longer be accounted for being representative for the primordial field.

4. Magnetic field strength and structure

Polarized thermal emission by aligned non-spherical grains is the main source of polarized submillimeter radiation in Bok globules (e.g., Weintraub et al. 2000, Greaves et al. 1999). Irrespective of the alignment mechanism, charged rotating interstellar grains would have a substantial magnetic moment, leading to a rapid precession of the grain angular momentum around the magnetic field direction (Draine & Weingartner 1997). This implies a net alignment of the grains with the magnetic field. Based on the work by Chandrasekhar & Fermi (1953), the dispersion of polarization position angles is thought to be
Table I. Masses, gas densities, polarization, and magnetic field strengths of the envelopes. (a) Frerking et al. 1987. (b) Wang et al. 1995; Launhardt et al. 1996. (c) Wang et al. 1995. (d) RMS turbulence velocity of a large sample of nearby star-forming Bok globules derived from C$^{18}$O (J=2-1).

| Object         | $\rho_{\text{Gas}}$ [g cm$^{-3}$] | $v_{\text{turb}}$ [km s$^{-1}$] | $\sigma_\gamma$ [°] | $B$ [µG] |
|----------------|----------------------------------|---------------------------------|---------------------|---------|
| B 335 (CB 199) | 8.6E-18                           | 0.14                            | 0.02$^a$            | 35$^\circ$14$^d_9$ | 134$^a_4$6$^b_9$ |
| CB 230 (L 1177)| 3.6E-18                           | 0.29                            | 0.04$^b$            | 29$^\circ$8$^a_8$4 $^d_6$ | 218$^a_5$56 |
| CB 244 (L 1262, SE core) | 8.0E-18                           | 0.29$^c$            | 33$^d_9$19$^c_2$   | 257$^a_6$11$^d_9$ |
| CB 26 (L 1439) | 8.6E-19                           | 0.25$^d$            | 18$^a_7$16$^b_7$4 $^d_6$ | 144$^a_6$91 |
| CB 54          | 3.4E-19                           | 0.65$^c$            | 42$^d_6$11$^c_3$  | 104$^a_7$24$^b_4$ |

Inversely proportional to the magnetic field strength,

$$B = \frac{4\pi}{3} \rho_{\text{Gas}} \frac{v_{\text{turb}}}{\sigma_\gamma} :$$

Here, $B$ is the magnetic field strength in units of G, $\rho_{\text{Gas}}$ is the gas density (in units of g cm$^{-3}$), $v_{\text{turb}}$ the rms turbulence velocity (in units of cm s$^{-1}$), and $\sigma_\gamma$ the standard deviation to the mean orientation angle $\gamma$ of the polarization vectors (in units of radians). The resulting magnetic field strengths are in the range of 100–260 µG (see Tabl. I).

The comparison between the magnetic field structure and morphologic features of the globules, such as their elongation and outflow direction, reveals following correlations: First, the dense cores in B 335 and CB 230 are slightly elongated whereby the major axes are oriented almost perpendicular to the direction of the bipolar molecular outflows. Second, in the Class 0 source harbouring Bok globules B 335, CB 230, and CB 244, the outflows are oriented almost perpendicular to the mean direction of the magnetic field as seen in projection on the plane of the sky. In contrast, the directions of the magnetic field and outflow are aligned more parallel in the massive globule core CB 54 and in CB 26 with an embedded more evolved Class I source. We want to remark that the statistical significance of the latter is low because of the large scattering of polarization directions measured in CB 54 and the small number of polarization vectors and low spatial resolution in the case of in CB 26.

5. Conclusions

We presented 850 µm polarimetric observations of dense envelopes around the very high-density protostellar condensations in five selected Bok globules. In each object we found polarization degrees of several percent which
decrease towards the cores of the globules. Since the functional dependence of this behavior between the intensity and polarization is very similar for each globule, the optical properties of the grains do not seem to play a key role for the observed polarization decrease, but merely the coupling of the magnetic field to the grains.

Using the formalism by Chandrasekhar & Fermi (1953) we derive an estimate of the mean magnetic field strengths in these globules on the order of several hundred $\mu$G. These magnetic field strengths are well above those of the interstellar medium (see, e.g., Myers et al. 1995) but comparable to typical magnetic field strengths found in molecular clouds, pre-protostellar cores, and other star-forming regions.

We find the direction of the polarization vectors/magnetic field, the elongation of the Bok globules, and the orientation of the outflows (in the case of CB 26: potential outflow direction along the lobes) to be related to one another. In particular, we find the mean magnetic field direction of the Bok globules with embedded Class 0 sources – B 335, CB 230, and CB 244 – to be oriented almost perpendicular to the outflow axis. In contrast to this, the magnetic field is nearly aligned with the potential outflow direction of CB 26, harbouring a more evolved Class I source.

Our findings suggest that the mean magnetic field direction in a protostellar envelope changes from initially perpendicular to the outflow axis to a more moderate inclination at the end of the main accretion/outflow phase. However, a larger sample of protostellar sources in different evolutionary stages has to be investigated to confirm this preliminary conclusion.

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**References**

Berry, D.S., Gledhill, T.M. 1999, Starlink UserNote 223
Brand, J., Blitz, L. 1993, A&A, 275, 67
Cabrit, S., Goldsmith, P. F., Snell, R. L. 1988, ApJ, 334, 196
Chandler, C. J., Gear, W. K., Sandell, G., Hayashi, S., Duncan, W. D., Griffin, M. J., Hazella, S. 1990, MNRAS, 243, 330
Chandler, C.J., Sargent, A.I. 1993, ApJ, 414, L29
Chandrasekhar S., Fermi E., 1953, ApJ 118, 113
Draine, B.T., Weingartner, J.C. 1997, ApJ, 480, 633
Fiege, J.D., Pudritz, R.E. 2000a, ApJ, 534, 291
Fiege, J.D., Pudritz, R.E. 2000b, MNRAS, 311, 105
Ferking, M. A., Langer, W. D., Wilson, R. W. 1987, ApJ, 313, 320
Glenn, J., Walker, C.K., Young, E.T. 1999, ApJ, 511, 812
Greaves, J.S., Holland, W.S., Minchin, N.R., Murray, A.G., Stevens, J.A. 1999, A&A, 334, 668
Henning, Th., Wolf, S., Launhardt, R., Waters, R. 2001, ApJ, 561, 871
Hirano, N., Kameya, O., Nakayama, M., Takakubo, K. 1988, ApJl, 327, L69
Holland, W.S., Robson, E.I., Gear, W.K., Cunningham, C.R., Lightfoot, J.F., et al. 1999, MNRAS, 303, 659
Houde, M., Bastien, P., Dotson, J.L., Dowell, C.D., Hildebrand, R.H., et al. 2002, ApJ, 569, 803
Jenness, T., Lightfoot, J.F. 1998, in ASP Conf. Ser. 145, Astronomical Data Analysis Software and Systems VII, ed. R. Albrecht, R.N. Hook, & H.A. Bushouse, (San Francisco: ASP), 216
Keene, J., Davidson, J. A., Harper, D. A., Hildebrand, R. H., Jaffe, D. T., Loewenstein, R. F., Low, F. J., Pernic, R. 1983, ApJl, 274, L43
Kun, M. 1998, ApJs, 115, 59
Launhardt, R. 1996, Ph.D. Thesis, Univ. of Jena
Launhardt, R. 2001, In “Birth and Evolution of Binary Stars”, Reipurth B. & Zinnecker H. (eds.), Proceedings of IAU Symposium No. 200, p. 117
Launhardt, R., Evans, N.J., Wang, Y., Clemens, D.P., Henning, Th., Yun, J.L. 1998, ApJSS, 119, 59
Launhardt, R., Henning, Th. 1997, A&A, 326, 329
Launhardt, R., Mezger, P.G., Haslam, C.G.T., et al. 1996, A&A, 312, 569
Launhardt, R., Sargent, A. 2001, ApJ 562, L173
Launhardt, R., Ward-Thompson, D., Henning, Th. 1997, MNRAS, 288, L45
Matthews, B.C., Wilson, C.D. 2002, ApJ, 574, 822
Myers, P.C., Fuller, G.A., Goodman, A.A., Benson, P.J. 1991, ApJ, 376, 561
Myers, P.C., Goodman, A.A., Gusten, R., Heiles, C. 1995, ApJ, 442, 177
Ryden, B.S. 1996, ApJ, 471, 822
Tomita, Y., Saito, T., Ohtani, H. 1979, PASJ, 31, 407
Wang, Y., Evans, N.J.II, Zhou, S., Clemens, D.P. 1995, ApJ, 454, 217
Weintraub, D.A., Goodman, A.A., Akeson, R.L. 2000, in Protostars and Planets IV, ed. V. Mannings, A.P. Boss, & S.S. Russell (Tucson: Univ. Arizona Press), 247
Wolf, S., Launhardt, R., Henning, Th. 2003, ApJ, in press
Yun, J.L., Clemens, D.P. 1994a, ApJS, 92, 145
Yun, J.L., Clemens, D.P. 1994b, AJ, 108, 612