ABSTRACT

Using the Submillimeter Common-User Bolometer Array (SCUBA) at the James Clerk Maxwell Telescope (JCMT), we obtained submillimeter polarization maps of the Bok globules B335, CB 230, and CB 244 at 850 μm. We find strongly aligned polarization vectors in the case of B335 and CB 230, indicating a strong coupling of the magnetic field to the dust grains. Based on the distribution of the orientation and strength of the linear polarization, we derive the magnetic field strengths in the envelopes of the globules: 134 (B335), 218 (CB 230), and 257 μG (CB 244). In agreement with previous submillimeter polarization measurements of Bok globules, we find polarization degrees of several percent, decreasing toward the centers of the cores. Furthermore, we compare the magnetic field topology with the spatial structure of the globules, in particular with the orientation of the outflows and the orientation of the nonspherical globule cores. In the case of the globules B335 and CB 230, the outflows are oriented almost perpendicular to the symmetry axis of the globule cores. The magnetic field, however, is aligned with the symmetry axis of the prolate cores in the case of the Bok globules B335 and CB 230, while it is slightly aligned with the outflow axis in the case of the Bok globules CB 26 and CB 54. We discuss the possibility that the different orientations of the magnetic field relative to the outflow directions reflect different evolutionary stages of the single globules.

Subject headings: ISM: individual (B335, CB 230, CB 244) — ISM: magnetic fields — magnetic fields — polarization — submillimeter

1. INTRODUCTION

Bok globules are excellent objects to study the earliest processes of star formation. They are small in diameter (0.1–2 pc) and simply structured, and they are relatively isolated molecular clouds (Clemens, Yun, & Heyer 1991) with masses of 2–100 \( M_\odot \) (Bok 1977; Leung 1985). Low-mass star formation was found to be a common phenomenon in Bok globules. Many globules have bipolar molecular outflows (see, e.g., Yun & Clemens 1994a) and infrared colors and submillimeter properties that are consistent with Class 0 protostars or embedded Class I sources (Yun & Clemens 1994b; Launhardt & Henning 1997, hereafter LH97; Henning & Launhardt 1998).

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. In the case of Bok globules, this has been demonstrated for the first time by Henning et al. (2001, hereafter Paper I). Based on comprehensive preparatory studies, such as submillimeter continuum and CS line surveys (LH97; Henning & Launhardt 1998; Launhardt, Ward-Thompson, & Henning 1997; Launhardt et al. 1998; R. Launhardt et al. 2003, in preparation), polarization maps of three Bok globule cores (CB 26, CB 54, and CG 30) had been obtained with the Submillimeter Common-User Bolometer Array (SCUBA) at 850 μm. It was found that the magnetic field strengths derived from polarization patterns are well above those of the interstellar medium (Myers et al. 1995), but are similar to those found in other molecular cloud cores and protostellar envelopes (Bhatt & Jain 1992; Levin et al. 2001; Davis et al. 2000; Glenn, Walker, & Young 1999; Itoh et al. 1999; Minchin & Murray 1994; Chrysostomou et al. 1994; Crutcher 1999). The polarization pattern itself revealed striking similarities between the different globules. The degree of polarization amounts to several percent and decreases toward the centers of the dense cores.

Here, we present and discuss new polarization measurements at 850 μm of protostellar cores in three other nearby Bok globules: B335 (CB 199), CB 230, and CB 244. As for the previously observed Bok globules, it was our aim to prove basic correlations between the structure and strength of the magnetic field and the dust density distribution that have been investigated theoretically, e.g., by Padoan et al. (2001), Heitsch et al. (2001), Fiege & Pudritz (2000a, 2000c), and Basu & Mouschovias (1995). By combining intensity and polarization maps, the dust density distribution and the magnetic field structure can be found. Because of this enlargement of the sample of spatially resolved polarization maps of Bok globules, the observations were aimed to contribute to the solution of the following problems:

1. Are there systematic differences in the structure and strength of the magnetic field in the envelopes around low-mass young stellar objects at different evolutionary stages?
2. Do we see evidence that the magnetic field dominates the structure of globules? At which stage of evolution does the gas decouple from the magnetic fields?
In § 2 we compile the main results of previous investigations of our sources. In § 3 we give a brief overview of the performed observations and the subsequent data reduction procedure. The polarization maps are presented in § 4.1; magnetic field strengths are derived in § 4.2, followed by a discussion on the relation between the polarization degree and the intensity in § 4.3. Finally, we investigate the correlation between the magnetic field structure and morphological features of the individual globules in § 4.4.

2. SOURCE DESCRIPTION

In Paper I we investigated submillimeter polarization maps of the Bok globules CB 26, CB 54, and CG 30. In this paper we present new polarization measurements of the Bok globules B335 (CB 199), CB 230, and CB 244. These six globule cores are the strongest millimeter continuum sources from surveys by LH97 and Henning & Launhardt (1998) accessible with the James Clerk Maxwell Telescope (JCMT) SCUBA. They are the best-studied star-forming Bok globules.

B335 (CB 199) is an isolated, nearly spherical Bok globule at a distance of ~250 pc (Tomita, Saito, & Ohtani 1979; Frerking, Langer, & Wilson 1987). It accommodates one of the best-studied low-mass protostellar cores (see, e.g., Myers, Evans, & Ohashi 2000). The deeply embedded Class 0 protostar of \( L_{\text{bol}} \sim 3 L_\odot \) drives a collimated bipolar outflow with a dynamical age of \( \sim 3 \times 10^4 \) yr (Keene et al. 1983; Hirano et al. 1988; Cabrit, Goldsmith, & Snell 1988; Chandler et al. 1990; Chandler & Sargent 1993). The dense core in B335 is generally recognized as the best protostellar collapse candidate, and the emission from different molecular lines has been successfully modeled in terms of an inside-out collapse (Shu 1977) with infall age of \( \sim 10^5 \) yr and a current protostar mass of \( \sim 0.4 M_\odot \) (Zhou et al. 1993; Choi et al. 1995). Recent molecular line observations, made with higher angular resolution, show possible discrepancies with the predictions of inside-out collapse (Wilner et al. 2000).

From our SCUBA maps, we derive a total envelope mass of \( \sim 4 M_\odot \) within a radius of \( 1.5 \times 10^4 \) AU (R. Launhardt et al. 2003, in preparation). The small C\(^{18}\)O line widths, observed by Frerking et al. (1987), imply a turbulent velocity dispersion of only \( 0.14 \pm 0.02 \) km s\(^{-1}\) in the dense core.

CB 230 (L1177) is a small, bright-rimmed Bok globule associated with the Cepheus flare molecular cloud complex. While in earlier papers we suggested a distance of 450 pc (LH97), Kun (1998) pointed out that L1177 is more likely associated with an absorbing sheet at 300 pc. We therefore use a distance of 400 \pm 100 pc. The globule contains a binary protostellar core with \( 10^4 \) separation (east-west) and signatures of mass infall, which is associated with a double near-infrared (NIR) reflection nebula. Both protostars are associated with an NIR reflection nebula, and they drive separate aligned molecular outflows, but only the western one is associated with a massive accretion disk (Launhardt et al. 1998; Launhardt 2001). The total mass and luminosity of the protostellar double core, which is unresolved in our SCUBA maps, are \( \sim 7 M_\odot \) within a radius of \( 2 \times 10^4 \) AU and \( \sim 10 L_\odot \), respectively (Launhardt 2001; R. Launhardt et al. 2003, in preparation). The dynamical age of the collimated large-scale outflow is \( \sim 2 \times 10^4 \) yr (Yun & Clemens 1994a). From the observed C\(^{18}\)O line width of 0.7 \pm 0.1 km s\(^{-1}\) (Wang et al. 1995; Launhardt 1996), we calculate an upper limit for the turbulent velocity dispersion of \( 0.29 \pm 0.04 \) km s\(^{-1}\).

CB 244 (L1262) is an isolated Bok globule located at a distance of 180 pc and probably associated with the Lindblad ring (LH97; Kun 1998). It contains two dense cores separated by \( \sim 90^\circ \). The more prominent southeastern core, which we observed here, contains a Class 0 protostar with signatures of mass infall. It is associated with a bipolar molecular outflow with a dynamical age of \( \sim 10^4 \) yr (Yun & Clemens 1994a; Wang et al. 1995; Launhardt 1996; LH97; Launhardt et al. 1997). The total mass and bolometric luminosity of this protostellar core are \( \sim 2 M_\odot \) within a radius of \( 1.8 \times 10^4 \) AU and \( \sim 1.5 L_\odot \), respectively (Wang et al. 1995; R. Launhardt et al. 2003, in preparation). The C\(^{18}\)O line width and turbulent velocity dispersion are the same as for CB 230, i.e., \( \sigma_{\text{turb}} \sim 0.29 \) km s\(^{-1}\).

3. OBSERVATIONS AND DATA REDUCTION

The observations were performed at the 15 m JCMT on Mauna Kea (Hawaii) between 2001 September 10 and 14. The effective beam size (HPBW) is \( \sim 14^\prime \) at 850 \( \mu \)m. Polarimetry was conducted using SCUBA (Holland et al. 1999) and its polarimeter, SCU-POL, with the 350–850 \( \mu \)m achromatic half-wave plate. For a detailed description of the polarimeter hardware, we refer to Murray et al. (1997) and Greaves et al. (2000).

Since our targets have a protostellar core/disk-envelope structure with envelope sizes smaller than \( 2R \), we used the imaging mode of SCUBA. Fully sampled 16 point jiggle maps have been obtained for each object, whereby each jiggle map was repeated 16 times with the wave plate turned by 22.5° between individual maps. This mode allows simultaneous imaging polarimetry with a 2:3 field of view in the long- \( (750–850 \mu \text{m}) \) and short- \( (350–450 \mu \text{m}) \) wavelength bands. However, only 850 \( \mu \)m data are presented in this paper, because the signal-to-noise ratio was too low for the 450 \( \mu \)m polarimetry data.

The data reduction package SURF (SCUBA User Reduction Facility; see Jenness & Lightfoot 1998) was used for flat-fielding, extinction correction, sky-noise removal (see Jenness, Lightfoot, & Holland 1998), and instrumental polarization correction. The Stokes parameters \( I, Q, \) and \( U \) were computed for each set of 16 maps using the POLPACK data reduction package (Berry & Gledhill 1999), by averaging maps taken at the same wave plate orientation and then fitting a sine wave to each image pixel. This set of Stokes parameters was then averaged and binned (over a 9° region) before the average linear polarization degree \( P_I \) and position angle \( \gamma \) for each pixel were calculated.

Since the chop throw was 120°, the very outer regions in the jiggle maps (which are also undersampled) may suffer from chopping into the outermost envelope regions and into extended low-level emission from the tenuous outer regions of the globules. We therefore restrict the polarization analysis to the inner region with a radius of \( 60^\prime \) of the maps and do not use the outer \( \sim 20^\prime \). Based on the 1.2 mm continuum maps obtained by R. Launhardt et al. (2003, in preparation), we arbitrarily chose a chop throw (azimuthal direction) for B335 and CB 230, while CB 244 was observed by chopping almost perpendicular to the axis defined by the main and the secondary components, in order to avoid the secondary component (see Fig. 1 for illustration and Tables 1 and 2 for properties of the globules).
We restrict the polarization analysis to regions in which the total flux density is higher than 5 times the rms in the maps (measured outside the central sources). Pixels in which the scatter of the total flux density measurements between different jiggle cycles was larger than 20% of the average value were also excluded. Furthermore, polarization vectors with $P_l/\sigma(P_l) < 3$, where $\sigma(P_l)$ is the standard deviation of the polarization degree, have been excluded. We found that our selection criteria, which are based on signal-to-noise ratios, result in polarization maps that agree well with those obtained with the default restrictions of ORACDR/POLPACK, which uses absolute thresholds ($0.1\% < P_l < 15\%$ and $\sigma < 10\%$).

4. RESULTS

4.1. Polarization Maps

Polarized thermal emission by aligned nonspherical grains is the main source of polarized submillimeter radiation in Bok globules (see, e.g., Weintraub, Goodman, & Akeson 2000; Greaves et al. 1999). The polarization maps of the Bok globules B335, CB 230, and CB 244 at 850 $\mu$m are shown in Figure 1.

In Figure 2 we plot the polarization histogram for each globule. The degree of linear polarization reaches values up to 14%, taking into account that the distributions $N(P_l)$ are strongly influenced by statistical noise due to the small number of data points. The mean percentages of polarization degree for B335, CB 230, and CB 240 are 6.2%, 7.8%, and 5.1%, respectively. The corresponding $1/\sigma_\gamma$ dispersions are 3.7%, 4.1%, and 3.6%. These values are similar to those published in Paper I for the Bok globules CB 26, CB 54, and CG 30 (for polarization measurements in larger molecular clouds, see Dowell 1997, Novak et al. 1997, Hildebrand 1996, Hildebrand et al. 1993, Morris et al. 1992, and Gonatas et al. 1990).

4.2. Magnetic Fields

An estimate of the magnetic field strength (in gauss) can be derived from the polarization maps as follows (see Chandrasekhar & Fermi 1953):

$$B = |B| = \sqrt{\frac{4\pi}{3} \rho_{\text{Gas}} \frac{\nu_{\text{turb}}}{\sigma_\gamma}}.$$  

Here, $\rho_{\text{Gas}}$ is the gas density (in units of g cm$^{-3}$), $\nu_{\text{turb}}$ 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 radians). Hereby, it is assumed that the magnetic field is frozen in the cloud material. For a detailed discussion of the applicability of this equation, we refer to § 5.3 of Paper I.

Since the gas density $\rho_{\text{Gas}}$ obviously strongly increases toward the center of each core, the magnetic field strength should be derived as a function of the radial distance from the density center. However, the small number of polarization vectors fulfilling the selection criteria discussed in § 3 (see also Table 3) does not allow us to perform a statistical analysis on individual subsamples of polarization data points. Therefore, we decided to base our magnetic field estimates on the mean density from which the 850 $\mu$m emission at a certain projected distance from the emission center arises. To ensure that the density value represents the region...
from which \( \sigma \), was calculated, we used the mean distance of all considered polarization vectors from the center. These angular distances are 16\( \arcsec \) for B335, 21\( \arcsec \) for CB 230, and 13\( \arcsec \) for CB 244 (southeastern core).

We calculate the hydrogen number density profiles by using a ray-tracing code to fit spherically symmetric source models with an outer power-law density gradient to the observed, circularly averaged intensity maps. The model maps were convolved with the observed beam shape, and chopping was accounted for. The mean dust temperature in the envelopes was determined by the 450\( \mu m \) chopping was accounted for. The mean dust temperature in the envelopes was determined by the 450\( \mu m \) surface brightness ratio, under the assumption that the dust opacity index \( \beta = -1.8 \) and \( \kappa_{\text{dust}}(1.3 \text{ mm}) = 0.5 \text{ cm}^2 \text{ g}^{-1} \). Dust temperatures in the range 10–14 K with an unresolved, warmer core were derived, except for CB 26 and CB 54, which have higher temperatures and a global radial temperature gradient. Details of the models will be given in a forthcoming paper (R. Launhardt et al. 2003, in preparation). The derived envelope dust temperatures agree well with the kinetic gas temperatures derived by Cecchi-Pestellini, Casu, & Scappini (2001) for a number of very similar southern Bok globules with protostellar cores. They also agree with the outer envelope temperature Evans et al. (2001) calculate for starless globules, which are heated interstellar radiation fields only.

The dust emissivity is converted into hydrogen number density by using a standard hydrogen-to-dust mass ratio of 100. Details of the model will be given in a forthcoming paper (R. Launhardt et al. 2003, in preparation). To account for helium and heavy elements, we derive the total gas density \( \rho_{\text{Gas}} \) by

\[
\rho_{\text{Gas}} = 1.36 n_{\text{H}} M_{\text{H}},
\]

where \( M_{\text{H}} = 1.00797 \text{ amu} \) is the mass of a hydrogen atom. The corresponding densities are listed in Table 3.

The next quantity to be derived from the polarization map in order to achieve an estimate of the magnetic field strength is the standard deviation of the orientation angle, \( \sigma_{\gamma} \). The histograms of the orientation angle and the resulting standard deviations are shown in Figure 3 and compiled in Table 3. Using CB 230 as an example, Figure 4 also illustrates that a clear convergence toward a constant value of both quantities could be achieved on the basis of 18 complete polarization measurement cycles (“exposures”). For comparison, 27 and 15 exposures have been obtained for the globules B335 and CB 244, respectively.

The error estimate for the value of the standard deviation of the mean orientation angle \( \sigma_{\gamma} \) is based on a \( \chi^2 \) test, assuming a standard Gaussian distribution of the orientation angles. The error intervals given in Table 3 are based on confidence intervals for \( \sigma_{\gamma} \). The probability for the real (unknown) \( \sigma_{\gamma,\text{real}} \) to be included in this interval amounts to 95%. Based on this error estimate for \( \sigma_{\gamma} \), we give error intervals for the magnetic field strength \( B \).

The magnetic fields—determined by the application of equation (1)—are \( B_{\text{B335}} \approx 130, B_{\text{CB230}} \approx 220, \) and \( B_{\text{CB244}} \approx 260 \mu G \). According to the investigations of theoretical models of polarized dust emission from protostellar cores by Padoan et al. (2001), these values might have to be corrected by a factor of \( f \approx 0.4 \) in order to provide a better estimate of the average magnetic field strength in the cores.

In Paper I, we used volume-averaged densities, which are by a factor of about 3 \( (CB \ 54), 4 \) (CB 26), and 9 (DC 253—1.6) lower than those derived with our method applied here. For the sake of consistency and comparability, we rederive densities and magnetic field strengths for these three sources and give the corrected values in Table 3. The magnetic field strengths in all six considered Bok globules are therefore very similar, amounting to \( \approx 0.1–0.3 \text{ mG} \). These magnetic field strengths are in the range of those found in molecular clouds, pre-protostellar cores, and other star-forming regions (see, e.g., Matthews & Wilson 2002; Levin et al. 2001; Davis et al. 2000; Crutcher 1999; Glenn et al. 1999; Itoh et al. 1999; Minchin & Murray 1994; Chrysostomou et al. 1994; and Bhatt & Jain 1992).

### 4.3. \( P_l \) versus \( I \) Behavior

Similarly to previous polarization measurements in other star-forming cores (see, e.g., Matthews & Wilson 2002; Houde et al. 2002; Minchin, Bonifacio, & Murray 1996; Glenn et al. 1999; see also Paper I), the degree of polarization was found to decrease toward regions of increasing...
intensity (see Fig. 5). This behavior can be explained by either (1) an increase of the density in the brighter cores, resulting in an increased collisional disalignment rate of the grains toward the centers of the cores, (2) grain growth in the denser regions, resulting in unpolarized reemission by grains toward the centers of the cores, (2) grain growth in regions with high density and turbulence, and therefore the magnetic field strength, than we could give in Paper I. To combine the data, the six separate intensity distributions have been normalized according to equation (3). We find the following parameters: $a_0 = -1.70$, $a_1 = 3.96$, and $d_2 = -0.43$ for the best fit of equation (3) to the total data set (see Fig. 6). In fact, the average fit values for the entire sample are very similar to those found for GB 54 and DC 253−1.6 (see Paper I).

We remark that equation (3) represents an ad hoc assumption about the relation between the polarization degree $P_l$ and the corresponding intensity $I$, introduced to allow a first-order quantitative comparison of this relation for different Bok globules. A similar dependency, $P_l(I)$, was also found for other Bok globules and star-forming regions (Matthews & Wilson 2002; Houde et al. 2002; Minchin et al. 1996; Glenn et al. 1999; see also Paper I). A first qualitative confirmation of this observationally found nonlinear dependency was provided by Padoan et al. (2001), on the basis of MHD simulations assuming no alignment of grains in regions with $A_V > 3$ mag. A dependency in the form $P_l(n(r), v_{\text{turb}}(r))$ is, in fact, expected if the decrease of the polarization degree is due to an increased disalignment rate of the dust grains in regions of high density and turbulence velocity.

### 4.4. Correlation between the Magnetic Field Structure and the Morphology of the Bok Globules

All three globules (B335, CB 230, and CB 244) contain Class 0 protostellar cores and drive collimated bipolar molecular outflows (Chandler & Sargent 1993; Yun & Clemens 1994a; Launhardt 2001). Our polarization maps reveal alignment of polarization vectors, and therefore the magnetic field, with the outflow direction (most prominent in the case of B335). Thus, the question arises whether the outflow direction is somehow related to the magnetic field.

### TABLE 3

**MASSES, GAS DENSITIES, POLARIZATION, AND MAGNETIC FIELD STRENGTHS OF THE ENVELOPES**

| Object                  | $M_{env}$ ($M_\odot$) | $\langle n_H \rangle$ (cm$^{-3}$) | $\rho_{\text{Gas}}$ (g cm$^{-3}$) | $v_{\text{turb}}$ (km s$^{-1}$) | $N_{\text{nc}}$ (deg) | $\gamma$ (deg) | $\sigma_\gamma$ (deg) | $B$ (G) |
|-------------------------|-----------------------|----------------------------------|----------------------------------|-------------------------------|-----------------------|-------------------|---------------------|--------|
| B335                    | 5                     | 3.8E6                            | 8.6E−18                          | 0.14 ± 0.02                  | 20                    | -8.70            | 35.8 ± 14.4        | 134.49  |
| CB 230                  | 7                     | 1.6E6                            | 3.6E−18                          | 0.29 ± 0.04                  | 33                    | 23.5             | 29.8 ± 12.1        | 218.45  |
| CB 244 (southeastern core) | 1.5                  | 3.5E6                            | 8.0E−18                          | $\approx 0.29$               | 12                    | 68.3             | 33.1 ± 10.3        | 257.31  |
| CB 24d                  | 0.27                  | 3.6E5                            | 8.6E−19                          | 0.25                         | 7                     | 25.3             | 18.9 ± 7.3         | 144.28  |
| CB 54d                  | 100                   | 1.5E5                            | 3.4E−19                          | 0.65                         | 41                    | -68.0            | 42.7 ± 11.1        | 104.54  |
| DC 253−1.6d             | 9                     | 2.2E6                            | 5.0E−18                          | 0.25                         | 49                    | 14.4             | 38.2 ± 8.6         | 172.36  |

*Frerking et al. 1987.
Wang et al. 1995; Launhardt 1996.
Wang et al. 1995.
Rederived mean density ($n_H$) and corrected value for the magnetic field strength $B$.
No direct value available; rms turbulence velocity of a large sample of nearby star-forming Bok globules derived from C$^{18}$O ($J = 2−1$).
The magnetic field given for DC 253−1.6 in Table 2 of Paper I has to be corrected to $58_{-0.11}^{+0.13}$ G.
structure given by the polarization maps. Since for two of our previously investigated globules (CB 26 and CB 54; see Paper I) we also know the outflow direction, we include these sources in our discussion here. The double core in DC 253–1.6 drives two nearly perpendicular outflows and is therefore not considered here. In discussing the relative orientation and relation between the magnetic field and the outflow, one has to consider that only one component of the spatial orientation of the outflow ($v \sin i$) is known from velocity measurements and that the polarization vectors only allow tracing the projection of the magnetic field on the plane of the sky. In our analysis we assume that the magnetic field is oriented perpendicular to the measured polarization pattern. This widely applied concept is based on the finding that, irrespective of the alignment mechanism, charged interstellar grains would have a substantial magnetic moment leading to a rapid precession of the grain angular momentum $J$ around the magnetic field direction $B$, which implies a net alignment of the grains with the magnetic field (see, e.g., Draine & Weingartner 1997).

The 850 μm polarization maps overlaid with the blue- and redshifted outflow velocity contour lines of B335, CB 230, CB 244, CB 26, and CB 54 are shown in Figures 7, 8, and 9. Since the outflows have been mapped using different radio telescopes, the spatial resolution varies strongly, but the main features, i.e., the orientation with respect to the aligned polarization vectors, can be clearly seen.

**B335 (Fig. 7, left).**—This globule displays nearly parallel alignment of the polarization vectors (and therefore the mean polarization) with the outflow axis. The globule is clearly elongated in the north-south direction (see Fig. 1) and therefore oriented perpendicular to the polarization pattern and parallel to the magnetic field. Based on investigations of axis ratios of large samples of Bok globules, Myers et al. (1991) and Ryden (1996) found that oblate cores would be inconsistent with the observed axis ratios to a high confidence level. Thus, we assume that B335 is a prolate globule, rather than an oblate one seen edge-on. The orientation of the magnetic field parallel to the symmetry axis of the globule fits into the scenario described by Fiege & Pudritz (2000a; see also Fiege & Pudritz 2000c), assuming the case $B_z/B_\phi > 0.37$, where $B_z$ and $B_\phi$ are, respectively, the poloidal and toroidal magnetic field components at the outer surface of the globule core. Their theoretical investigations of molecular cloud cores that originate from filamentary clouds threaded by helical magnetic fields show that the radial pinch of the toroidal field component helps to squeeze cores radially into a prolate shape while helping to support the gas along the axis of symmetry. In the context of star formation inside Bok globules, it is of interest that the Bonnor-Ebert critical mass is reduced by about 20% by the toroidal field. Assuming that the predicted submillimeter polarization patterns for filamentary clouds are valid for elongated Bok globules as well, we cannot completely confirm the predictions by Fiege & Pudritz 2000b (see their Fig. 1 for different magnetic field/polarization pattern scenarios). Based on model simulations, these authors find depolarization along the axis of the filaments. While we find
depolarization toward the center of the Bok globules as well (see § 4.3 for a detailed analysis of this effect), the radial dependence of the polarization degree in the outer regions of the Bok globules does not agree with the theoretical findings for filamentary structures.

**CB 230 (Fig. 7, right).**—Alignment of the mean polarization is almost parallel to the outflow axis. The decrease of the linear polarization toward the bright globule core is slightly stronger toward the redshifted side of the lobe. The globule is slightly elongated in the east-west direction and therefore, as in the case of B335 (under the assumption of a spheroidal shape), elongated perpendicular to the polarization pattern and parallel to the magnetic field direction.

**CB 244 (Fig. 8, left).**—There is apparent alignment of the polarization vectors between the dominant southeastern core and the northwestern source, parallel to the density enhancement between both sources. If more highly resolved polarization maps with a sufficient, statistically larger sample of polarization vectors in this region will confirm this finding, it would support the hypothesis of matter infall along magnetic field lines during the initial stage of molecular cloud collapse.

Close to the main (southeastern) source, however, the orientation of the polarization vectors seems to change slightly, toward a preferential direction parallel to the outflow axis and therefore perpendicular to the orientation of the dust/gas “bridge” between the sources. One has to consider that the orientations of the small number of polarization vectors in the southeastern core show a large scatter. A more highly resolved polarization map would be required in order to confirm the change of the polarization/magnetic field orientation toward the southeastern core. This would also help to decide whether the magnetic field is aligned with the outflow (and therefore oriented in the same direction as in the region of the density enhancement between both sources) or if the outflow and/or other processes related to the ongoing star formation process in the southeastern core cause(d) a change of the magnetic field orientation.

The core of CB 244 is slightly elongated in the east-west direction and therefore—in contrast to B335 and CB 230—more aligned with the mean polarization direction than perpendicular to it. However, if the change of the polarization within the southeastern core is real, a scenario similar to that described for the other two globules is expected.

**CB 54 (Fig. 8, right).**—This is a large Bok globule associated with the molecular cloud BBW 4 at a distance of about 1.1 kpc (Brand & Blitz 1993). In contrast to B335 and CB 230, the mean polarization direction is found to be almost perpendicular to the outflow axis. However, one has to consider that (1) the polarization pattern shows a large scatter in the orientation of the individual polarization vectors and (2) the much larger distance of the object (compared to the other investigated globules) does not allow us to resolve structures of comparable size; i.e., the orientation of the magnetic field on the scale as measured in the case of the other globules is not known. The polarization measurements trace a magnetic field structure that is extended much farther out into the surrounding interstellar space and may therefore be much more representative of the interstellar magnetic field structure in this region than of the local magnetic field structure of CB 54.

This globule is slightly elongated in a southeast-northwest direction, almost parallel to the direction of the mean polarization, which is in contrast to the Bok globules B335 and CB 230. However, because of the much higher spatial distance of CB 54, we cannot rule out that this globule consists of several substructures (smaller globule cores) that are not resolved in our intensity maps. This possibility is supported by the finding that a small, young NIR stellar cluster that was probably born in CB 54 is projected against the dense core of this globule (Yun 1996; Launhardt 1996).

**CB 26 (Fig. 9).**—This small, slightly cometary-shaped Bok globule at a distance of about 140 pc (R. Launhardt et al. 2003, in preparation) contains a small, bipolar NIR nebula that is associated with strong submillimeter/...
millimeter continuum emission. The star responsible for the reflection nebula (see Fig. 9, right-hand panel) is deeply embedded and not seen even at 2.2 \( \mu m \). No large-scale outflow was observed, but the edge-on circumstellar disk found by Launhardt & Sargent (2001), as well as the bipolar structure perpendicular to the disk midplane, suggests either the existence of an outflow in the plane of the sky (for which the velocity field could not be traced) or, at least, a very weak outflow. The orientation of the mean polarization differs by about 35° from the orientation of the disk. As in the case of CB 54, we find the mean polarization direction (northeast-southwest) to be slightly aligned perpendicular

Fig. 6.—Left: Scatter diagram showing the distribution of \( P_i \) vs. intensity \( I \) across Bok globules B335, CG 30, CB 54, CB 230, CB 240, and CB 244 (southeastern core). The data for CG 30, CB 26, and CB 54 have been taken from Paper I. The line represents the best fit of the function given in eq. (3). Right: Corresponding distribution of the polarization degree as a function of the hydrogen density (see § 4.3). If the measurements for CB 54 (triangles) were excluded from this plot, a nearly linear dependency between the polarization degree and gas density is revealed for densities \( \log_{10} n_H < 8 \). What distinguishes CB 54 from the other objects is the fact that it most likely contains several unresolved sources (see Paper I for a detailed description of this source).

![Figure 6](image1)

![Figure 7](image2)

Fig. 7.—SCUBA intensity maps (850 \( \mu m \)) of the Bok globules B335 and CB 230 with (1) isointensity contour lines for CB 230 (850 \( \mu m \); dotted lines) at levels 0.15%, 0.30%, 0.45%, 0.60%, 0.75%, and 0.90% of the maximum intensity \( I_{\text{max}} \) (for reasons of clarity, isointensity contour lines corresponding to the 850 \( \mu m \) SCUBA intensity map are not shown in the case of B335—see Fig. 1 [top] for this information); (2) polarization pattern (850 \( \mu m \), see Fig. 1 for details); and (3) \(^{13}\)CO (1–0) spectral channel maps obtained with the Owens Valley Radio Observatory. For B335, the white (gray) contour lines represent the spatially well separated blueshifted (redshifted) western (eastern) outflow lobe. The contours are spaced at 2 \( \sigma \) intervals of 200 mJy beam\(^{-1}\) (from Chandler & Sargent 1993; beam width: 2\(\prime\)9 \( \times \) 2\(\prime\)9). For CB 230, the solid (dashed) contour lines represent the spatially well separated blueshifted (redshifted) outflow lobe (beam width: 4\(\prime\)); in the blue lobe, \( v_{\text{LSR}} = 1.6, \ldots, 2.8\) km s\(^{-1}\) (solid contours), and in the red lobe, \( v_{\text{LSR}} = 3.0, \ldots, 4.2\) km s\(^{-1}\) (dashed contours). The step width amounts to 0.3 km s\(^{-1}\) for both lobes (from Launhardt 2001). See also Yun & Clemens (1994a, Fig. 27) for a large-scale outflow map (6\(\prime\) \( \times \) 6\(\prime\)).
Fig. 8.—SCUBA intensity maps (850 μm) of the Bok globules CB 244 and CB 54 with (1) isointensity contour lines (850 μm; thin solid lines) at levels 0.15%, 0.30%, 0.45%, 0.60%, 0.75%, and 0.90% of the maximum intensity $I_{\text{max}}$; (2) polarization pattern (850 μm; see Fig. 1 for details); and (3) $^{12}$CO (1–0) spectral line map (from Yun & Clemens 1994a). The broad solid (dashed) contour lines represent the blue (red) integrated line wing emission. These maps were obtained with a 15 beam receiver with an antenna having beam width of 48" (FWHM; for comparison, the SCUBA FWHM amounts to 14.7 at 850 μm). For CB 244, the blueshifted (redshifted) outflow contour lines begin with 0.5 (0.6) K km s$^{-1}$ and are stepped by 0.15 (0.2) K km s$^{-1}$. For CB 54, the blueshifted (redshifted) outflow contour lines begin with 1.7 (0.45) K km s$^{-1}$ and are stepped by 0.3 (0.15) K km s$^{-1}$.

Fig. 9.—Left: SCUBA intensity map (850 μm) of the Bok globule CB 26 with (1) isointensity contour lines (850 μm; dotted lines) at levels 0.15%, 0.30%, 0.45%, 0.60%, 0.75%, and 0.90% of the maximum intensity $I_{\text{max}}$ and (2) polarization pattern (850 μm; see Fig. 1 for details) (data from Paper I). Furthermore, the mean direction of the polarization $\gamma$ is shown. The range of $\gamma \pm \sigma_\gamma$ is marked. Right: $J$–$H$ color map of the bipolar NIR reflection nebula ($K$-band emission; black contours) in the central part of CB 26 (from Launhardt & Sargent 2001). The white contour lines show the protoplanetary disk discovered by Launhardt & Sargent (2001; contour levels: 4, 11, 18, 25, and 32 mJy arcsec$^{-2}$; data obtained with OVRO at 1.3 mm; beam width: 0.58 × 0.39).
to the outflow direction. The small number of polarization vectors does not allow us to trace the expected randomly oriented polarization vectors in the inner part of the globule.

The comparison with the results of an analytic investigation of the final states for a quasi-magnetostatic phase of the evolution of molecular cloud cores by ambipolar diffusion (based on a magnetized singular isothermal toroid model) by Li & Shu (1996) describes the scenario probably found in the case of CB 26. As their Figure 1 shows, an hourglass-shaped magnetic field structure is oriented perpendicular to an already formed (proto-)circumstellar disk. Taking into account the low resolution of our polarization maps, this magnetic field pattern translates into an almost parallel polarization pattern, with an orientation parallel to the disk and perpendicular to the outflow. Another prediction of their model is that at this stage, the magnetic field structure in the inner core would be very complex because of inflowing gas colliding with the expanding outflows. In agreement with our observations, the polarization vectors would be much more randomly oriented in the core. At this point, we would like to remind the reader that this discussion is based on a statistically very small number of polarization vectors only. A more highly resolved polarization map is required to confirm the conclusions drawn above.

We want to conclude with the most interesting findings concerning the connections between the magnetic field topology and Bok globule morphology of the globule cores (see also Table 4):

1. The globules B335 and CB 230 show a slightly elongated shape, which we assume in the following to be the projection of a prolate spheroid on the plane of the sky (in agreement with the theoretical and observational findings by Fiege & Pudritz 2000a, 2000c, Myers et al. 1991, and Ryden 1996, as discussed above). We exclude the CB 26 and CB 54 cores, which are also elongated, from this discussion. In contrast to the other sources, CB 26 is a remnant envelope around a young protostellar disk, and CB 54 is a large and massive globule that may contain multiple unresolved cores.

2. We find the direction of (a) the polarization vectors/magnetic field, (b) the elongation of the Bok globules, and (c) the orientation of the outflows (in the case of CB 26, potential outflow direction) to be not independent (i.e., arbitrarily oriented), but related to one another.

3. The direction of the outflows of B335 and CB 230 is almost perpendicular to the orientation of the elongation direction of the globules, i.e., perpendicular to the potential projection of the symmetry axis on the plane of the sky.

4. In the case of B335 and CB 230, the outflows are oriented almost parallel to the preferential direction of the linear polarization, i.e., perpendicular to the magnetic field (both as seen in projection on the plane of the sky).

5. In the case of CB 54 and CB 26, the outflows are oriented slightly perpendicular to the preferential direction of the linear polarization, i.e., parallel to the magnetic field. However, 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 CB 26, the statistical significance of these results is low. In the particular case of the globule CB 26, a spatially more highly resolved polarization map would be required to confirm the apparent alignment between the direction of the potential outflow direction and the magnetic field.

We exclude CB 244 from this overview, since we can hardly separate the magnetic field structure related to the density enhancement reaching from the main (southeastern) source to the secondary (northwestern) source from the magnetic field structure that dominates at the position of the main source alone.

We compared our polarization maps with those resulting from magnetohydrodynamic (MHD) simulations of molecular clouds performed by Padoan et al. 2001 (their Fig. 5; see also Fig. 5 of Heitsch et al. 2001, for comparison). In agreement with many of these simulations, our observations of B335, CB 230, and CB 26 show large-scale alignment of the polarization vectors with smooth changes of the orientation, also on a large scale only. Similar to the simulated polarization pattern in Figure 5d of Padoan et al. (2001), the change of the direction of the polarization vectors at the transition from the high-density Bok globule toward the lower density gas/dust bridge between the two cores in CB 244 can be seen. Furthermore, our observations of B335 and CB 230 show not only a decrease of the polarization degree (see § 4.3 for a detailed analysis), but also that the orientation of the polarization vectors does not remarkably change toward 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 chaotic, and we assume that it can no longer be accounted as being representative of the primordial field. Thus, one might expect that CB 26 represents a more evolved protostellar system than the globules B335 and CB 230. However, the data available so far, in particular the low-resolution, undersampled polarization map of CB 26, do not allow us to regard this assumption as a strong conclusion. A more highly resolved, better-sampled polarization map of CB 26 would help to confirm this hypothesis.

### TABLE 4

| Object      | Mean Magnetic Field Direction (deg) | Mean Outflow Orientation (deg) | Angle between Outflow and Magnetic Field Orientation (deg) |
|-------------|-----------------------------------|--------------------------------|----------------------------------------------------------|
| CB 26........ | -65 ± 19                          | -29^a,b                        | 36                                                        |
| CB 54........ | 22 ± 43                           | 30^b                           | 8                                                         |
| CB 230...... | -67 ± 30                          | 0^c,d                          | 67                                                        |
| B335 ......... | 3 ± 36                            | -80^e                          | 83                                                        |
| CB 244 ...... | -22 ± 33                          | 45^f                           | 67                                                        |

**Note.**—The error intervals given for the magnetic field directions are equivalent to the standard deviation to the mean orientation angle of the polarization (see Table 3 here and Table 2 in Paper I).

^a Launhardt & Sargent 2001.

^b P.A.(disk) = 60° ± 5° (Launhardt & Sargent 2001).

^c Yun & Clemens 1994a.

^d Launhardt 2001.

^e Hirano et al. 1988.
Spatially more highly resolved polarization maps would simultaneously allow us to test another theoretical prediction about the protostellar evolution, based on which the different orientations of the magnetic field relative to the outflow direction of B335 and CB 230, on the one hand, and CB 26, on the other hand, could be explained. Tomisaka (1998) showed, on the basis of MHD simulations of collapse-driven outflows in molecular cores, that the direction of the magnetic field lines and the disk plane decreases from $60^\circ$ to $70^\circ$ to $10^\circ$–$30^\circ$ during the evolution of the outflow (Figs. 2a and 2b in that work). At least on a large scale, our observations are in agreement with this scenario. Since our polarization maps do not resolve structures of the size of a circumstellar disk, the magnetic field direction as derived from the polarization maps would change from an orientation perpendicular to the disk midplane to an orientation parallel to the disk midplane during the evolution of the protostar, and of its outflow in particular.

5. CONCLUSIONS

Using the SCUBA at the JCMT, we obtained 850 $\mu$m polarization maps with a resolution of $9^\prime \times 9^\prime$ of the Bok globules B335, CB 230, and CB 244. We find polarization degrees equally distributed in the range $P_l = 0\%$–$14\%$. Using the formalism of Chandrasekhar & Fermi (1953), we derive an estimate of the mean magnetic field strengths in these globules in the order of several hundred microgauss. These values are slightly higher than those discussed in Paper I based on another sample of Bok globules ($B = 20$–$100$ $\mu$G), but they are still comparable to typical magnetic field strengths found in molecular clouds, preprotostellar cores, and other star-forming regions (see §4.2 for references). The magnetic fields derived here are higher because we based our calculations on a higher density closer to the globule centers for the magnetic field estimates (see §4.2).

We find a similar correlation between the polarization degree and the intensity, and therefore the density, of the emitting dust as measured in other star-forming cores (see §4.3 for references). We verify the nonlinear relation between these quantities first stated in Paper I. However, the particular equation used to parameterize the decrease of the polarization with increasing intensity (eq. [3]) is a first-order approximation only (see §4.3 and Fig. 6). MHD simulations show qualitatively similar results (Padoan et al. 2001), but a quantitative description of this phenomenon is still lacking. Here, different grain (dis-)alignment processes in the centers of Bok globules, such as those discussed in Paper I, will have to be considered in much more detail in these simulations (see, e.g., Lazarian 1997 and Lazarian, Goodman, & Myers 1997).

The main question we focused on in this work is related to the search for correlations between the structure of the magnetic field and particular features of Bok globules. In addition to the globules B335 and CB 230, we reconsider the globules CB 26 and CB 54 (from Paper I) as well. Because of the more complex structure of the Bok globule CB 244, this object is only partly considered in this investigation (see §4.4). Furthermore, CB 54 may represent an unresolved ensemble of Bok globules. As common criteria to characterize the main spatial structure of the Bok globules, we take into account (1) the orientation of the slightly elongated core (in the case of B335 and CB 230) and (2) the orientation of the outflow (or the expected outflow in the case of CB 26). Based on theoretical studies by Fiege & Pudritz (2000a, 2000c) and observational constraints by Myers et al. (1991) and Ryden (1996), we assume that these four globules all have a prolate shape rather than an oblate one.

We find that the outflows are oriented almost perpendicular to the symmetry axis of the globule cores in the case of the globules B335 and CB 230. The elongations found in the case of CB 54 and CB 26 have a similar orientation, but the lower (absolute) spatial resolution of CB 54 and the possible influence of a neighboring object on CB 26 may have changed the intrinsic globule shape. The magnetic field, however, is aligned with the symmetry axis of the prolate cores in the case of the Bok globules B335 and CB 230, while it is slightly aligned with the outflow axis in the case of the Bok globules CB 26 and CB 54. Since the symmetry axis of the core is expected to be aligned with the magnetic field in order to explain the observed high abundance of prolate Bok globules, we assume that the magnetic field structure found in the case of the globules B335 and CB 230 represents the primordial magnetic field, which is nearly undisturbed even in the innermost regions of these globule cores. The polarization decreases toward the centers of these cores, but the orientation of the linear polarization and therefore, perpendicular to it, the orientation of the magnetic field, is the same as on larger scales. The polarization maps of these two objects allow us to resolve structures with diameters of about $2 \times 10^3$ (B335) and $4 \times 10^3$ AU (CB 230). If the magnetic field structure in the circum-(proto-)stellar environment differs strongly from the large-scale magnetic field direction, these perturbations must occur on much smaller scales than given by the resolution of the polarization maps, in order to allow the net polarization to be aligned with the large-scale magnetic field structure. Furthermore, we cannot exclude the possibility that the magnetic field structure is very complex on scales much smaller than the resolution of the polarization maps. Then the net polarization arising from the inner core is likely to be negligible, and all we measure is the small contribution of polarized light from the foreground material.

Consistent with the results of hydrodynamic simulations by Tomisaka (1998) and theoretical investigations of the protostellar evolution by Li & Shu (1996), the orientation of the magnetic field relative to the outflow direction is not constant but changes during the evolution of the outflow/disk. Taking into account the comparably low resolution of our polarization maps, this change would result in

1. a polarization pattern that is oriented perpendicular to the outflow (mean magnetic field parallel to the outflow) at the beginning of the outflow, changing to
2. a negligible polarization in the range of the core due to polarization cancellation (averaging) effects at some point during the evolution of the outflow, and finally to
3. a polarization pattern that is oriented parallel to the outflow (mean magnetic field perpendicular to the outflow) at the late stage of the evolution of the outflow.

Within this frame, our results for the Bok globules B335 and CB 230 are consistent with an evolutionary stage somewhere between stages 2 and 3. Furthermore, the different relative orientation of the magnetic field to the outflow direction/circumstellar disk orientation in the case of CB 26
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