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Distortion of Magnetic Fields in the Dense Core SL 42 (CrA-E) in the Corona Australis **Molecular Cloud Complex**

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Abstract

The detailed magnetic field structure of the dense core SL 42 (CrA-E) in the Corona Australis molecular cloud complex was investigated based on near-infrared polarimetric observations of background stars to measure dichroically polarized light produced by magnetically aligned dust grains. The magnetic fields in and around SL 42 were mapped using 206 stars, and curved magnetic fields were identified. On the basis of simple hourglass (parabolic) magnetic field modeling, the magnetic axis of the core on the plane of the sky was estimated to be $40^{\circ} \pm 3^{\circ}$. The plane-of-sky magnetic field strength of SL 42 was found to be $22.4 \pm 13.9 \,\mu$ G. Taking into account the effects of thermal/turbulent pressure and the plane-of-sky magnetic field component, the critical mass of SL 42 was obtained to be $M_{\rm cr} = 21.2 \pm 6.6 M_{\odot}$, which is close to the observed core mass of $M_{\rm core} \approx 20 M_{\odot}$. We thus conclude that SL 42 is in a condition close to the critical state if the magnetic fields lie near the plane of the sky. Because there is a very low-luminosity object toward the center of SL 42, it is unlikely that this core is in a highly subcritical condition (i.e., the magnetic inclination angle is significantly deviated from the plane of the sky). The core probably started to collapse from a nearly kinematically critical state. In addition to the hourglass magnetic field modeling, the Inoue & Fukui mechanism may explain the origin of the curved magnetic fields in the SL 42 region.

Unified Astronomy Thesaurus concepts: Starlight polarization (1571); Infrared astronomy (786); Interstellar dust (836); Dense interstellar clouds (371); Interstellar magnetic fields (845)

1. Introduction

Studying magnetic fields associated with dense molecular cloud cores is important for revealing (1) the initial conditions of star formation, (2) the formation process of dense cores (i.e., structure formation in molecular clouds), and (3) the relationship between polarization and extinction (i.e., the alignment of dust grains with respect to magnetic fields). These problems are not well understood, because the observations to probe the physical properties of dense cores are difficult, particularly observations of magnetic fields. The lack of magnetic information on dense cores leads to a consequent lack of important information for the understanding of star formation.

A popular method to measure the plane-of-sky magnetic field direction is the measurement of linearly polarized light produced by magnetically aligned dust grains in thermal emission (far-infrared (FIR) to submillimeter) or in the dichroic extinction of background starlight passing through dust grains (optical to near-infrared (NIR)). The Davis-Chandrasekhar-Fermi method (Davis 1951; Chandrasekhar & Fermi 1953) is often employed to estimate the magnetic field strength of clouds or cores from these linear polarization data.

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The most significant error factor in conducting magnetic field studies is the line-of-sight inclination angle of the magnetic axis of dense cores ($\gamma_{\rm mag}).$ If a magnetic field experiences a distortion with an axisymmetric shape, e.g., hourglass-shaped fields (Kandori et al. 2017a, hereafter Paper I), we observe a significant depolarization pattern, particularly in the equatorial plane of the core, due to the crossing of polarization vectors at the front and rear sides of the core. The shape of the depolarization pattern depends on the magnetic inclination angle. The angle γ_{mag} can be determined by comparing polarimetric observations with a three-dimensional (3D) model calculated for various inclination angles (Kandori et al. 2017b, hereafter Paper II; see also Kandori et al. 2020e, hereafter Paper VI). Note that few methods can measure the $\gamma_{\rm mag}$ of dense cores. The depolarization pattern and magnetic inclination angle can be used to calibrate the observed polarization-extinction relationship (Kandori et al. 2018, hereafter Paper III; see also Paper VI).

Past studies that did not include $\gamma_{\rm mag}$ were unable to provide details on the magnetic field strength for each object, because the ambiguity when the inclination angle is not known is significant. With the knowledge of γ_{mag} based on the 3D analysis, we can discuss the universality and diversity of the magnetic field structure and total magnetic field strength of dense cores. To date, four low-mass dense cores with a known 3D magnetic field structure and total strength (FeSt 1-457: Paper I; Barnard 68: Kandori et al. 2020b; Barnard 335:

Kandori et al. 2020c; CB 81: Kandori et al. 2020a) have been identified. The NIR polarimetric survey of low-mass dense cores and Bok globules is still in its infancy, and we need more objects for systematic/statistical studies.

As part of our magnetic field survey of dense cores, we investigated the SL 42 core (Hardegree-Ullman et al. 2013) in the Corona Australis molecular cloud (CrA) using NIR polarimetry. The SL 42 core has many alternative designations, such as Cloud 42/S42/SLDN42 (Sandqvist & Lindroos 1976) and Core 5 (Yonekura et al. 1999). A clump including SL 42 is named CrA-E in Bresnahan et al. (2018) based on large-scale FIR mapping with Herschel. In this paper, we use the name SL 42 following Hardegree-Ullman et al. (2013).

The CrA complex exhibits an elongated "head-tail" morphology (e.g., Figure 1 of Bresnahan et al. 2018), having a dense "head" to the west and a diffuse "tail" to the east. Star formation is taking place in the head region. The tail region consists of a "north filament" and a "south streamer" (Bresnahan et al. 2018), and the SL 42 core is located in the middle of the north filament. The distance to the CrA complex was thought to about 130 pc (Casey et al. 1998; Neuhäuser & Forbrich 2008). However, recent results using the Gaia data have provided slightly more distant values of 154 ± 4 pc (Dzib et al. 2018) and 151 ± 8 pc (Zucker et al. 2019). In this paper, we will use 150 pc for the distance to the CrA complex.

The SL 42 core was observed with the Herschel satellite and the 15 m Swedish ESO Submillimeter Telescope (SEST; Hardegree-Ullman et al. 2013). The radius, mass, and central density of the core were $\approx 300'' = 0.23$ pc, $\approx 20 M_{\odot}$, and $\approx 1.0 \times 10^{6}$ cm⁻³, respectively. Because Hardegree-Ullman et al. (2013) used 130 pc for the distance to SL 42, we converted their physical quantities into values for a distance of 150 pc. The kinematic temperature of the core T_k was assumed to be 10 K. The density structure of the core was modeled using the Bonnor-Ebert sphere model (Ebert 1955; Bonnor 1956). The obtained best-fit Bonnor–Ebert parameter was $\xi_{\text{max}} \approx 25$ (i.e., center to edge density contrast of \approx 364), which is far greater than the critical value of $\xi_{max} = 6.5$, indicating that the core is unstable to gravitational collapse if there is no additional supporting force. The external pressure $P_{\rm ext}$ of the core was $(1.0 \times 10^6/364) \times T_{\rm k} = 2.8 \times 10^4 \,{\rm K \, cm^{-3}}$. The center of the core determined using a column density map based on Herschel was (R.A., decl.) = $(19^{h}10^{m}20.2^{\circ}, -37^{\circ}08'26.0^{\circ}, J2000)$ (Hardegree-Ullman et al. 2013). The N₂H⁺ (J = 1-0) line width was about 0.52 km s^{-1} , which provides a turbulent velocity dispersion σ_{turb} of 0.21 km s⁻¹. Note that we do not use the C¹⁸O (J = 2-1) data observed with the SEST telescope, because significant CO depletion was observed in SL 42 (Hardegree-Ullman et al. 2013). A very low-luminosity object (VeLLO) candidate was found toward the center of SL 42 in the Herschel 70 μ m data (Bresnahan et al. 2018). Note that a VeLLO is defined as a young object with internal luminosity of $\leq 0.1 L_{\odot}$ embedded in dense cloud cores (e.g., Young et al. 2004; Dunham et al. 2008; Kim et al. 2019). In addition, beyond the radius of SL 42 (7!4 from the center of the core), there is a weak-line T Tauri star H α 16 at (R.A., decl.) = $(19^{h}06^{m}23^{s}.8, -37^{\circ}09'18.''0, J1950)$ (Marraco & Rydgren 1981; Batalha et al. 1998; Gregorio-Hetem & Hetem 2002).

In this study, wide-field background star polarimetry at NIR wavelengths was conducted for SL 42. The plane-of-sky magnetic field structure was revealed using stars in and around

the core radius. The total magnetic field strength of the core was estimated based on the Davis–Chandrasekhar–Fermi method (Davis 1951; Chandrasekhar & Fermi 1953) and 3D magnetic field modeling of the core. Using the resulting magnetic field information, the kinematical stability and the formation scenario of SL 42 is discussed.

2. Observations

The NIR polarimetric observations of the SL 42 core region in the CrA cloud complex were conducted using the IRSF 1.4 m telescope and *JHKs* simultaneous polarimeter SIRPOL (Kandori et al. 2006, see also Nagayama et al. 2003 for camera module). IRSF/SIRPOL provides a large field of view (7!7 × 7!7 with a scale of 0!"45 pixel⁻¹), which enable us to cover nearby dark cloud cores with a single telescope pointing. SIRPOL is a single-beam polarimeter, which consists of a rotating half-wave plate and a wire-grid polarizer.

The fluctuations of the measured polarization degree during exposures are typically $\approx 0.3\%$. The instrumental polarization over the field of view is confirmed to be less than 0.3%. The uncertainty of the zero-point angle of the polarimeter is less than 3% (Kandori et al. 2006; Kusune et al. 2015). A polarized standard star RCrA#88 was observed on 2017 July 13 to obtain $P_H = 2.82\% \pm 0.09\%$ and $\theta_H = 91^\circ.9 \pm 0^\circ.9$, which are consistent with data in the literature ($P_H = 2.73\% \pm 0.07\%$, $\theta_H = 92^\circ \pm 1^\circ$; Whittet et al. 1992).

Observations of SL 42 (mosaic of 10 images) were conducted on the nights of 2017 June 14, 21, 23, 25, and 29, and July 3, 4, 6, 7, and 11. Exposures of 15 s were performed at four half-wave plate angles, in the sequence of 0°, 45°, 22°.5, and 67°.5, at 10 dithered positions (one set). Total exposure time was 1500 s (10 sets) for each half-wave plate angle. Typical seeing conditions were $\approx 1.^{"}4$ (≈ 3 pixels) at *H*.

The acquired data were reduced using the Interactive Data Language (IDL). Following the methods described in Kandori et al. (2007), we performed dark subtraction, flat correction, and frame combine after registration. We obtained a combined image of Stokes *I* and four images combined with respect to the half-wave plate angle of $I_{0^{\circ}}$, $I_{45^{\circ}}$, $I_{22^{\circ},5}$, and $I_{67^{\circ},5}$. Twilight flat was used to calibrate these observations, and we confirmed that the process did not produce false signals or instrumental polarizations (Kandori et al. 2020a).

Point sources with a peak greater than 10σ from the local sky background were cataloged on the Stokes I image. Using the cataloged positions of stars, aperture polarimetry was performed on the I_{0° , I_{45° , $I_{22^\circ,5}$, and $I_{67^\circ,5}$ images. We set the aperture radius to be the same as the FWHM of each mosaic image, and the sky radius and the width of the sky annulus were set to 10 and 5 pixels, respectively. A relatively small aperture size was used in order to avoid stellar flux contamination in a crowded field. We did not employ the point-spread function fitting photometry, because relative photometry is important in polarimetry. The goodness of fits can vary on each half-wave plate angle image, and this causes the systematic error in polarimetric measurements. The stars with the photometric uncertainty of greater than 0.1 mag were removed from the list. A total of 4319 sources were detected in the H band. The limiting magnitudes were 18.0 mag in the H band.

The Stokes parameters for each star were derived from the equations $I = (I_0 + I_{45} + I_{22.5} + I_{67.5})/2$, $Q = I_0 - I_{45}$, and $U = I_{22.5} - I_{67.5}$. The polarization degree *P* and angle θ were



Figure 1. Column density map based on the Herschel satellite (André et al. 2010; Bresnahan et al. 2018). The region surveyed with NIR polarimetry is enclosed by the white line.

obtained with $P = \sqrt{Q^2 + U^2}/I$ and $\theta = 0.5$ atan (U/Q). *P* tends to be overestimated particularly for low signal-to-noise ratio data. To correct this effect, we used $P_{\rm db} = \sqrt{P^2 - \delta P^2}$ (Wardle & Kronberg 1974). We use a debiased *P* for the discussion of polarization in the following.

In the present study, we discuss the results obtained in the H band for which dust-extinction effects are less severe than in the J band, and the polarization efficiency is greater than in the K_s band.

3. Results and Discussion

3.1. Distortion of Magnetic Fields

Figure 1 presents the finding chart of our observations. The background image is the column density map based on the Herschel data (André et al. 2010; Bresnahan et al. 2018). The SL 42 region is located near the center of the image, and our IRSF/SIRPOL observation region is enclosed by the white line. Figure 2 shows the observed polarization vectors (yellow lines) on the Stokes *I* mosaic image in the *H* band. Polarization vectors generally flow from northeast to southwest. The most significant feature on the vector map is the curved structure in the polarization vectors, which is particularly prominent in the center to the southern part. There is a slightly curved structure in the northernmost part of the mosaic image. Figure 3 is the same as Figure 2 but the background image is the Herschelbased column density map and the white circle shows the radius (300'') of the SL 42 core (Hardegree-Ullman et al. 2013).

There are at least two possible interpretations of the curved magnetic field structure. At a glance, the southern curved field structure seems to be associated with the SL 42 core. The magnetic field lines appear to wrap around the core. This resembles a mechanism proposed by Inoue & Fukui (2013) in which the interaction between a shock wave and the core can create a bending magnetic field structure. Another possibility is the existence of hourglass-shaped fields with a magnetic center offset from the center-of-mass distribution. We observed a similar geometry in the CB 81 core in the Pipe Nebula (Kandori et al. 2020b). In this case, a nonuniform initial density or magnetic field distribution can be compressed by turbulence or shocks to create an "offset hourglass field structure." In this study, we first model the data using the offset hourglass field in

both 2D and 3D. Then, we will discuss the possibility of the Inoue & Fukui (2013) mechanism in Section 3.4.

Figure 4 shows schematic figures for these two scenarios. In the figure, the white lines show the magnetic field line, and the red plus signs show the center of the core. The background image shows the column density distribution. In panels (a) and (b) of Figure 4, the magnetic field lines darken toward the lower-left corner. In panel (a), this corresponds to the small polarization degree due to a depolarization effect prominent in the steep field curvature part. In panel (b), this corresponds to a decrease of the winding magnetic fields because a shock wave arrives from the direction of the upper-right corner and the direction of the lower-left corner is behind the core.

In each panel of Figure 4, we used the function $y = g + gCx^2$ to draw the magnetic field lines. In the function, g specifies each magnetic field line and C determines the steepness of the curvature of the parabolic function. Because g is included in the second term, the steepness of the curvature increases with distance from the x-axis. For panel (a), the feature is consistent with the analytically described hourglassshaped magnetic field model (Mestel 1966; Ewertowski & Basu 2013; Myers et al. 2018). For panel (b), the function $y = g + Cx^2$ may provide a better description of the wrapping of magnetic fields around the edge-on cylinder. However, the present study, as well as the study by Hardegree-Ullman et al. (2013), assumes that the SL 42 core is spherical in shape. In this case, wrapping of the magnetic fields also occurs at the front and rear of the core, which results in a field component with a polarization direction parallel to the direction of the shock wave. The parallel field is superimposed on the wrapping magnetic fields of the core, so that the curvature of the magnetic field lines located at the rear of the core against the shock wave can be steeper than $y = g + Cx^2$. Thus, for describing this configuration, we concluded that the function $y = g + gCx^2$ is better than $y = g + Cx^2$. Note that the function to model the Inoue & Fukui (2013) mechanism depends on both the density structure of the blob and the viewing angle (e.g., see Reissl et al. 2018; Tahani et al. 2019). The function form presented here is just a simple representation of the bending field shape predicted by Inoue & Fukui (2013).

On the basis of the discussion above, we obtained similar curved magnetic field geometries for the (a) offset hourglass and (b) Inoue–Fukui mechanism as shown in Figure 4. The



Figure 2. Polarization vectors of point sources superimposed on the mosaic intensity image in the *H* band. Stars for which $P_H \ge 0.5\%$ and $P_H/\delta P_H \ge 5$ are shown. The scale bar above the image indicates 5% polarization.

southeast part in the field geometry is the same for (a) and (b). If the northwest field component is prominent, we can conclude that scenario (a) is plausible, because scenario (b) cannot create such a structure. If not, it is not easy to discriminate between them. In this case, there are two possible scenarios. We discuss the two scenarios in Section 3.4 to assess the origin of the curved magnetic fields.

Figure 5 shows the P_H versus $H - K_s$ (i.e., A_V) relationship. To estimate A_V , we assumed a region of decl. $\ge -36^{\circ}56'$ as an extinction-free reference field, and obtained 0.155 mag as the average $H - K_s$ color of stars in the reference field. The value is close to the average $H - K_s$ color of typical field stars (0.15 mag, Lada et al. 1994). All stars with $H - K_s \ge 0.7$ mag are located within the radius of SL 42. A linear fitting to these stars resulted in a slope of $2.71\% \pm 0.31\%$ mag⁻¹ (dashed line in Figure 5). If we include all the source in the fitting, the resulting slope is $13.56\% \pm 0.63\%$ mag⁻¹ (dotted line), which is close to the upper limit of the polarization efficiency for the interstellar medium (≈ 14 , Jones 1989). Note that the distribution of all the stars is distorted, and it may not be good to fit them using linear fitting, which assumes homoscedastic Gaussian scatter. Therefore, the dotted line in Figure 5 is just a reference. In Figure 5, there are several stars with a high P_H (\gtrsim 5%) and without a large A_V (\lesssim 5 mag). Though these sources are included in the 2D and 3D magnetic field analysis, they do not affect the conclusion because their number is small compared with the whole sample (N = 206).

3.2. Parabolic Model

Figure 6 shows the configuration of the magnetic field (solid white lines) estimated using a parabolic function and its shift and rotation. In the figure, 206 polarization vectors having $P_H \ge 0.5\%$ and $P_H/\delta P_H \ge 5$ are included. For the parabolic function, $y = g + gCx^2$ was used, where g specifies the magnetic field lines and C determines the degree of curvature. θ_{mag} is the position angle of the magnetic field direction (from north through east). Note that we used the parabolic function in the 90° rotated form so that, when θ_{mag} is 0°, the direction corresponds to the direction of the decl. The best-fit parameters were determined to be $\theta_{mag} = 40^{\circ} \pm 3^{\circ}$ and $C = 5.0(\pm 0.3) \times 10^{-6} \, \mathrm{arcsec}^{-2}$.

A parabolic function was employed because this is the simplest form of approximating the analytically described hourglass-shaped magnetic field model (Mestel 1966; Ewertowski & Basu 2013;



Figure 3. Polarization vectors of point sources in the *H* band superimposed on the column density map based on Herschel. The region surveyed with NIR polarimetry is enclosed by the dashed white line. The core radius (300") is indicated by the white circle, and the center of SL 42 is shown by the red plus sign. The green plus sign indicates the young star H α 16. The scale bar above the image indicates 5% polarization.







Figure 4. Schematic figures to explain the origin of the curved magnetic fields (white lines) observed toward SL 42. (a) Offset hourglass, with an offset angle between the center of mass (red plus sign) and the center of the hourglass-shaped magnetic fields (blue plus sign). The structure can be generated by the accumulation of an initially nonuniform medium dragging magnetic fields. (b) Inoue & Fukui (2013) mechanism. A shock wave propagates from the upper-right corner to the lower-left corner, sweeping the magnetic fields, and the magnetic fields wrap around the core to create the curved magnetic field structure. In both figures, the darkness of the contour refers to the expected polarization level.

Myers et al. 2018; see also Paper VI for a comparison of the parabolic function to the hourglass model). Note that the bending field structure in the southeastern part of the figure resembles the model by Inoue & Fukui (2013).

In the fitting procedure, the observational error associated with each star was taken into account when calculating

$$\chi^2 = \sum_{i=1}^n \frac{(\theta_{\text{obs},i} - \theta_{\text{model}}(x_i, y_i))^2}{\delta \theta_i^2},$$
(1)

where *n* is the number of stars, *x* and *y* are the coordinates of these stars, θ_{obs} and θ_{model} denote the polarization angles from observations and from the model, and $\delta\theta_i$ is the observational error. The coordinate origin of the parabolic function is R.A. = 19^h09^m42[§]46, decl. = -36°59′26″.5 (J2000), determined by searching for the minimum χ^2 for the variables *x* and *y* in and around the core. The center coordinate of the core (the peak of the column density distribution based on Herschel) is R.A. = 19^h10^m20[§]2, decl. = -37°08′26″.0 (J2000). The



Figure 5. Relationship between the polarization degree and $H - K_s$ color toward the background stars. Stars for which $P_H/\delta P_H \ge 4$ are plotted. The dashed line and dotted line denote linear fits to the stars with $H - K_s \ge 0.7$ mag and to all the stars.



Figure 6. Polarization vectors of point sources in the H band superimposed on the column density map based on Herschel. The region surveyed with NIR polarimetry is enclosed by the dashed white line. The center of SL 42 is shown by the red plus sign. The blue plus sign indicates the center of the hourglass-shaped magnetic fields. The white lines indicate the direction of the magnetic field inferred from the parabolic fitting. The scale bar above the image indicates 5% polarization.



Figure 7. Polarization vectors of point sources in the H band superimposed on the offset angle map. In each grid box with 300" width, the average angle differences between the observations and the parabolic model were calculated. The white lines indicate the direction of the magnetic field inferred from the parabolic fitting. The scale bar above the image indicates 5% polarization.

angular distance between these two centers is 11.72, which roughly corresponds to one core diameter (10').

The parabolic fitting was satisfactory, as the standard deviation of the residual angles, $\theta_{res} = \theta_{obs} - \theta_{fit}$, was smaller when using the parabolic function ($\delta\theta_{\rm res} = 28^\circ.9$) than in the case of a uniform field ($\delta\theta_{\rm res} = 55^{\circ}.0$). However, a closer look at the data reveals that there are areas where the model and observations deviate systematically. This leads to an overestimate of the standard deviation of the residual angle. Thus, we divided the stars using the coordinate grid with 300" width in the R.A. and decl. direction, and calculated the mean θ_{res} in each grid box. The result is shown in Figure 7. The values were treated as an offset deviation angle in each box and subtracted from the θ_{res} values of stars falling in each box. We found 17°.43 for the offset-subtracted $\delta\theta_{\rm res}$ value. Because the grid size is the same as the radius of the core, we believe that we are subtracting a sufficiently large structure in this analysis. Figure 8 shows the histogram of the offset-subtracted θ_{res} . Employing 600" (core diameter) and 150" (1/2 core radius) for grid size, we obtained 25°.23 and 11°.66 for $\theta_{\rm res}$. We thus used δ° as the uncertainty of the offset-subtracted $\delta\theta_{\rm res}$. The intrinsic dispersion, $\delta\theta_{\rm int} = (\delta\theta_{\rm res}^2 - \delta\theta_{\rm err}^2)^{1/2}$, estimated using the parabolic fitting, was found to be 17°.15 (0.299 radian), where $\delta\theta_{\rm err}$ is the standard deviation of the observational error in the polarization measurements.

The polarization vectors used to obtain the above polarization angle dispersion values include the vectors located outside of core's boundary. We thus check the angle dispersion using the stars falling inside the core radius (25 stars) and obtained the offset-subtracted $\theta_{\rm res}$ as 12°.58, 16°.28, and 18°.87 for the grid width of 150″, 300″, and 600″, respectively. Therefore, the value of $\theta_{\rm res} = 17°.43 \pm 8°.00$ employed above includes the polarization angle dispersion for the core. Note that in the angle dispersion calculation, outliers with more than a 45° angle deviation (three out of 25 vectors) were rejected.

Assuming frozen-in magnetic fields, the intrinsic dispersion of the magnetic field direction, $\delta\theta_{int}$, can be attributed to the perturbation of the Alfvén wave by turbulence. The strength of the plane-of-sky magnetic field (B_{pos}) can be estimated from the relationship $B_{\rm pos} = C_{\rm corr} (4\pi\rho)^{1/2} \sigma_{\rm turb} / \delta\theta_{\rm int}$, where ρ and σ_{turb} are the mean density of the core and the turbulent velocity dispersion (Chandrasekhar & Fermi 1953), and $C_{\text{corr}} = 0.5$ is a correction factor suggested by theoretical studies (Ostriker et al. 2001; see also, Heitsch et al. 2001; Padoan et al. 2001; Heitsch 2005; Matsumoto et al. 2006). Using the mean density $(\rho = 3.11 \times 10^{-20} \text{ g cm}^{-3})$ and turbulent velocity dispersion $(\sigma_{\text{turb}} = 0.21 \text{ km s}^{-1})$ from Hardegree-Ullman et al. (2013) and $\delta\theta_{\rm int}$ derived in this study, we obtained $B_{\rm pos} = 22.4 \,\mu {\rm G}$. For error estimation, we assumed that the turbulent velocity dispersion and mean density values were accurate within 30%. Thus, the uncertainty in B_{pos} was estimated to be 13.9 μ G. Note that the uncertainty of 8° of $\delta\theta_{res}$ is included in the error calculation.

3.3. 3D Magnetic Field

The 3D magnetic field modeling was performed following the same procedure described in a previous paper (Section 3.1 of Paper VI). The 3D version of the simple parabolic function, $z(r, \varphi, g) = g + gCr^2$ in the cylindrical coordinate system (r, z, φ) was used to model the core magnetic fields, where g specifies the magnetic field lines, C is the curvature of the lines, and φ is the azimuth angle (measured in the plane perpendicular to r). Using this function, the magnetic field lines are axially symmetric around the r axis.

In the model, the amount of polarization per unit volume was assumed to be proportional to the mass in the volume. For the



Figure 8. Histogram of the residuals for the observed polarization angles after subtraction of the angles obtained by parabolic fitting (θ_{res}) and its average angle offset measured in a 300" width box.

density structure of the core, we employed the Bonnor–Ebert sphere with the solution parameter of $\xi_{max} = 25$ (Hardegree-Ullman et al. 2013). The orientation of polarization generated by dust grains in each cell was assumed to be parallel to the orientation of magnetic field at the location of the cell.

The 3D model was virtually observed after rotating in the line-of-sight (γ_{mag}) and the plane-of-sky (θ_{mag}) directions. γ_{mag} is the line-of-sight inclination angle measured from the plane of the sky. In this procedure, the Stokes parameters in each cell of the model core were integrated toward the line of sight. The analysis was performed in the same manner described in Section 3.1 of Paper VI. The resulting polarization vector maps for the 3D parabolic model for various γ_{mag} are shown in Figure S1 of Paper VI.

Since the polarization distributions in the model core differ from one another depending on the viewing angle toward the line of sight, the χ^2 fitting of these distributions with the observational data can be used to restrict the line-of-sight magnetic inclination angle and 3D magnetic curvature.

Figure 9 summarizes the distribution of χ^2_{θ} calculated using the model and observed polarization angles as

$$\chi_{\theta}^{2} = \sum_{i=1}^{n} \frac{(\theta_{\text{obs},i} - \theta_{\text{model}}(x_{i}, y_{i}))^{2}}{\delta \theta_{i}^{2}},$$
(2)

where *n* is the number of stars, *x* and *y* show the coordinates of stars, θ_{obs} and θ_{model} denote the polarization angle from observations and the model, and $\delta\theta_i$ is the observational error. The optimal magnetic curvature parameter, *C*, was determined at each inclination angle γ_{mag} to obtain χ^2_{θ} . From the polarization angle fitting, it is clear that a small

From the polarization angle fitting, it is clear that a small inclination angle ($\gamma_{mag} \leq 50^{\circ}$) and pole-on geometry

 $(\gamma_{\rm mag} = 90^{\circ})$ are unlikely. The distribution of χ^2_{θ} is relatively flat for the region $60^{\circ} \gtrsim \gamma_{\rm mag} \gtrsim 85^{\circ}$, and there is a minimization point at $\gamma_{\rm mag} = 80^{\circ}$. Though the estimated 1σ uncertainty is 8°, we conclude that $\gamma_{\rm mag}$ is 75° with an uncertainty of 15°. The best magnetic curvature obtained at $\gamma_{\rm mag} = 75^{\circ}$ was $2.87 \times 10^{-6} \, {\rm arcsec}^{-2}$.

It is notable that the χ^2 values in Figure 9 are very large (about 6×10^4). The value is still large if it is divided by the number of stars (N = 206). We tried to fit the large-scale hourglass-shaped structure, and in addition to the observational error, each data point has a scatter from Alfvén waves. In the Equation (2), we included the observational error in the denominator of the χ^2 equation, but we could not include the scatter caused by Alfvén waves. That is why we obtained large χ^2 values. In Section 3.2, we obtained the intrinsic scatter caused by Alfvén waves as $\delta\theta_{int} = 17^{\circ}.15$. If we include the square of the value in the denominator of the Equation (2) and further divide Equation (2) by the number of stars (N = 206), we obtained the reduced $\chi^2 = 2.21$ at the minimization point.

Figure 10 shows the best-fit 3D parabolic model along with the observed polarization vectors. The background image is the column density map of the model core processed using the line integral convolution (LIC) technique (Cabral & Leedom 1993). We used the publicly available IDL code developed by Diego Falceta Gonçalves. The direction of the LIC "texture" is parallel to the magnetic field direction. The direction of the model vectors generally agrees with the observations. The standard deviation of the differences in the plane-of-sky polarization angles between the 3D model and the observations is $15^{\circ}.32$, which is close to the offset-subtracted (measured with 300'' grid) $\delta\theta_{res}$ value.



Figure 9. χ^2 distribution of the polarization angles (χ^2_{θ}). The best magnetic curvature parameter (*C*) was determined at each γ_{mag} . $\gamma_{mag} = 0^{\circ}$ and 90° correspond to the edge-on and pole-on geometry in the magnetic axis.



Figure 10. Best-fit 3D parabolic model with observed polarization vectors (yellow vectors). The background image was generated using the line integral convolution (LIC) technique (Cabral & Leedom 1993). The direction of the LIC "texture" is parallel to the direction of the magnetic fields. The background image is based on the column density of the model core. The scale bar above the image indicates 5% polarization.



Figure 11. Polarization vectors of point sources in the H band superimposed on the column density map based on Herschel. The region surveyed with NIR polarimetry is enclosed by the dashed white line. The center of SL 42 is shown by the red plus sign. The white lines indicate the direction of the magnetic field inferred from the parabolic fitting. These are rough approximations that take into account the characteristics of the Inoue & Fukui (2013) model. The scale bar above the image indicates 5% polarization.

3.4. Magnetic Properties of the Core and the Origin of the Curved Magnetic Fields

Here, we estimate and discuss the core's magnetic properties, first without 3D correction (plane-of-sky component) and then considering the validity of 3D correction based on the inclination angle obtained using the offset hourglass modeling.

The plane-of-sky magnetic field strength averaged for the whole core was determined to be 22.4 \pm 13.9 μ G in Section 3.2. The magnetic support of the core against gravity can be investigated using the parameter $\lambda = (M/\Phi)_{obs}/(M/\Phi)_{critical}$, which represents the ratio of the observed mass-to-magnetic flux ratio to a critical value, $(2\pi G^{1/2})^{-1}$, suggested by theory (Mestel & Spitzer 1956; Nakano & Nakamura 1978). Based on the plane-of-sky magnetic field strength, we determined a value of $\lambda = 2.0 \pm 0.7$ (i.e., magnetically supercritical). The magnetic critical mass of the core of 9.9 \pm 4.7 M_{\odot} was lower than the observed core mass of $M_{core} \approx 20 M_{\odot}$. Note that this does not necessarily imply the gravitational collapse of the core, because there are additional thermal/turbulent pressure components.

The critical mass of SL 42, taking into account both magnetic and thermal/turbulent support effects is $M_{\rm cr} \simeq M_{\rm mag} + M_{\rm BE}$ (Mouschovias & Spitzer 1976; Tomisaka et al. 1988; McKee 1989) and was determined to be 9.9 + 11.3 = 21.2 ± 6.6 M_{\odot} , where $M_{\rm BE} = 11.3 \pm 4.7 M_{\odot}$ is the Bonnor-Ebert mass calculated using an assumed kinematic temperature of 10 K, a turbulent velocity dispersion of 0.21 km s⁻¹ (equivalent to a temperature of 13 K, calculated from Hard-egree-Ullman et al. 2013), and an external pressure of 2.86 × 10⁴ K cm⁻³ (calculated from Hardegree-Ullman et al. 2013). The estimated $M_{\rm cr}$ value is comparable to the observed core mass $M_{\rm core}$, indicating that SL 42 is in a nearly critical

state if the direction of the magnetic fields lies in the plane of the sky.

The relative importance of magnetic fields with respect to the support of the core was investigated using the ratios of the thermal and turbulent energy to the magnetic energy, $\beta \equiv 3C_s^2/V_A^2$ and $\beta_{turb} \equiv \sigma_{turb,3D}^2/V_A^2 = 3\sigma_{turb,1D}^2/V_A^2$, where C_s , σ_{turb} , and V_A denote the isothermal sound speed at 10 K, the turbulent velocity dispersion, and the Alfvén velocity. These ratios were found to be $\beta = 0.83 \pm 0.56$ and $\beta_{turb} = 1.08 \pm 0.97$. Though uncertainties are large, the thermal, turbulent, and magnetic energies are consistent with being in equipartition, if the direction of magnetic fields is in the plane of the sky.

As noted in the introduction, a VeLLO candidate was found toward the center of SL 42 (Bresnahan et al. 2018). In addition, there is a weak-line T Tauri star H α 16 (Marraco & Rydgren 1981; Batalha et al. 1998; Gregorio-Hetem & Hetem 2002) in the vicinity of the core. It is thus reasonable to treat SL 42 as a protostellar core. SL 42 is in a nearly kinematically critical state with the plane-of-sky magnetic field component. If the magnetic field inclination angle of SL 42 deviates from the plane of the sky, the physical status of SL 42 should be subcritical, which is not consistent with it being a protostar. Thus, from the magnetic properties of the core and the existence of young star(s), it is most likely that the SL 42 core is associated with nearly plane-of-sky magnetic fields, and the core has started a collapse from a nearly kinematically critical state. If this is true, the offset hourglass field scenario of SL 42, which provides a large inclination angle of $\gamma_{\rm mag} = 75^{\circ}$ in its 3D analysis in Section 3.3, is probably inaccurate.

Here, we derive the magnetic properties of SL 42 with a 3D correction based on the hourglass modeling. The inclination correction factor is $1/\cos 75^\circ = 3.86$. The total magnetic field



Figure 12. Magnetic field map of the CrA complex. The region surveyed with NIR polarimetry is enclosed by the white line. The background image was generated using the line integral convolution (LIC) technique (Cabral & Leedom 1993). The direction of the LIC "texture" is parallel to the direction of the magnetic fields. The background image is based on the Stokes *I* image of the Planck data (353 GHz). The resolution of the image is 5'.

strength averaged for the whole core is $B_{\text{tot}} = 86.45 \,\mu\text{G}$, which is very strong for a mean density of 3.11×10^{-20} g cm⁻³ $(7.99 \times 10^3 \text{ cm}^{-3})$. The ratio of the mass-to-magnetic flux ratio to the critical value λ is 0.52, suggesting that SL 42 is in a magnetically subcritical state. The critical mass of the core is $M_{\text{cr}} \simeq M_{\text{mag}} + M_{\text{BE}} = 49.4 \, M_{\odot}$, where $M_{\text{mag}} = 38.1 \, M_{\odot}$ and $M_{\text{BE}} = 11.3 \, M_{\odot}$, indicating a subcritical state for SL 42. For energy comparison, $\beta = 0.06 \pm 0.03$ and $\beta_{\text{turb}} = 0.07 \pm 0.06$. Based on these results, the magnetic field is extremely strong and maintains the core as being subcritical, and for energy equipartition, the extremely strong magnetic fields imbalance the distribution of the energy. Though it is possible that SL 42 is a peculiar core, these quantities do not fit with the existence of young stars in and around SL 42.

For the scenario of a curved field in SL 42, another possibility is the Inoue & Fukui (2013) mechanism. Figure 11 shows the magnetic field distribution for scenario (b). As discussed in Section 3.1, the use of the function $y = g + gCx^2$ is reasonable to describe the plane-of-sky polarization vector distribution of SL 42. The expected direction of the shock wave

propagation is $\theta_{\text{shock}} \approx 130^{\circ}$, which is 90° from θ_{mag} . The θ_{shock} direction is roughly toward the Upper Centaurus Lupus OB association. The influence of the OB association on the CrA complex is shown and discussed in Bresnahan et al. (2018) and Harju et al. (1993). For scenario (b), the northern slightly curved magnetic component can be ignored in the fitting.

Figure 12 shows the global magnetic field structure $(8^{\circ} \times 8^{\circ})$ around the CrA complex based on 353 GHz dust polarization data taken by the Planck satellite. The box enclosed by the white line shows the surveyed region with the NIR polarization. Complex magnetic field structures are observed toward the CrA complex, although the resolution of the image is relatively large (5'). The direction of the magnetic fields is roughly east–west, which is roughly parallel to the orientation of the cloud complex (Planck Collaboration XXXV 2016). A bending structure is apparent in our surveyed region (white line), which can also be observed in our NIR polarimetry (see the center to the south region in Figure 2). From the Planck data, it is evident that there is a single curved

structure in our surveyed region. Thus, scenario (b) in Figure 4 may be more likely than scenario (a) based on the morphology of large-scale magnetic fields.

There are at least two scenarios for the explanation of the magnetic field distribution in and around the SL 42 core. Scenario (a) is the offset hourglass structure, and scenario (b) is the Inoue & Fukui (2013) mechanism.

The 3D analysis of the offset hourglass-shaped magnetic field structure (Section 3.2) resulted in a very subcritical condition. This result cannot explain the existence of young stars possibly associated with the SL 42 core. Though the SL 42 core might be a peculiar core, this is a weak point of scenario (a).

The 3D modeling of the Inoue–Fukui mechanism is not easy. In the model, the shock wave interacts with a dense core, and magnetic field lines at the surface of the core can change direction to wrap around the core. The white lines in Figure 11 are only a rough approximation that take into account the characteristics of the model. The comparison of the observations with theoretical simulations is beyond the scope of this paper. The incompleteness in the modeling based on the Inoue– Fukui mechanism is a weak point of scenario (b).

As discussed above, the choice of the line-of-sight magnetic inclination angle that is largely deviated from the plane of the sky can lead to the highly subcritical condition of the SL 42 core. This does not fit in the existence of young stars in and around SL 42. We thus expect a nearly plane-of-sky magnetic field geometry for SL 42, which can result in a nearly critical state.

4. Summary and Conclusion

The detailed magnetic field structure of the dense core SL 42 (CrA-E) in the Corona Australis molecular cloud complex was investigated based on NIR polarimetric observations of background stars to measure dichroically polarized light produced by magnetically aligned dust grains. The magnetic fields in and around SL 42 were mapped using 206 stars and curved magnetic fields were identified. Based on simple hourglass (parabolic) magnetic field modeling, the magnetic axis of the core on the plane of the sky was estimated to be $\theta_{\rm mag} = 40^{\circ} \pm 3^{\circ}$. The plane-of-sky magnetic field strength of SL 42 was found to be 22.4 \pm 13.9 μ G. Taking into account the effects of thermal/turbulent pressure and the plane-of-sky magnetic field component, the critical mass of SL 42 is found to be $M_{\rm cr} = M_{\rm mag} + M_{\rm BE} = 21.2 \pm 6.6 \ M_{\odot}$, which is close to the observed core mass of $M_{\rm core} \approx 20 \ M_{\odot}$. In the equation, the magnetic critical mass is $M_{\rm mag} = 9.9 \pm 4.7 M_{\odot}$ (magnetically supercritical) and the Bonnor-Ebert mass is $M_{\rm BE} = 11.3 \pm$ 4.7 M_{\odot} . We conclude that SL 42 is in a condition close to the critical state if the magnetic fields lie near the plane of the sky. Because there is a VeLLO toward the center of SL 42, it is unlikely that the core is in a highly subcritical condition (i.e., magnetic inclination angle significantly deviated from the plane of the sky). The core probably started to collapse from a nearly kinematically critical state. In addition to the hourglass magnetic field modeling, the Inoue & Fukui (2013) mechanism may explain the origin of the curved magnetic fields in the SL 42 region. The curved magnetic field structure could be created by a shock wave interacting with a dense blob with magnetic fields subsequently swept by the shock wrapping around the blob.

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