Two-component Magnetic Field along the Line of Sight to the Perseus Molecular Cloud: Contribution of the Foreground Taurus Molecular Cloud

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Abstract

Optical stellar polarimetry in the Perseus molecular cloud direction is known to show a fully mixed bimodal distribution of position angles across the cloud. We study the Gaia trigonometric distances to each of these stars and reveal that the two components in position angles trace two different dust clouds along the line of sight. One component, which shows a polarization angle of $-37^\circ\pm5^\circ$, has a higher polarization fraction of $2.0\pm1.7\%$, primarily traces the Perseus molecular cloud at a distance of 300 pc. The other component, which shows a polarization angle of $+66^\circ\pm19^\circ$ and a lower polarization fraction of $0.8\pm0.6\%$, traces a foreground cloud at a distance of 150 pc. The foreground cloud is faint, with a maximum visual extinction of $\leq1$ mag. We identify that foreground cloud as the outer edge of the Taurus molecular cloud. Between the Perseus and Taurus molecular clouds, we identify a lower-density ellipsoidal dust cavity with a size of 100–160 pc. This dust cavity is located at $l=170^\circ$, $b=-20^\circ$, and $d=240$ pc, which corresponds to an H I shell generally associated with the Per OB2 association. The two-component polarization signature observed toward the Perseus molecular cloud can therefore be explained by a combination of the plane-of-sky orientations of the magnetic field both at the front and at the back of this dust cavity.

Unified Astronomy Thesaurus concepts: Interstellar clouds (834); Starlight polarization (1571); Interstellar magnetic fields (845); Polarimetry (1278)

Supporting material: machine-readable table

1. Introduction

Interstellar magnetic fields ($B$-fields) are thought to play an important role in the formation of molecular clouds. As material from the interstellar medium (ISM) flows along field lines onto the nascent clouds, the resulting filamentary structures are expected to extend perpendicular to the interstellar $B$-field (see Hennebelle & Inutsuka 2019 for a review). However, this flow of matter can also influence the morphology of the surrounding $B$-field. Therefore, the $B$-field structures we observe around molecular clouds are imprinted with their history of an accumulation from the ISM, thus allowing us to trace the processes that led to their formation (e.g., Gómez et al. 2018).

The plane-of-sky (POS) component of the $B$-field can be traced by polarimetric observations of optical and near-infrared (NIR) radiation from stars located behind molecular clouds, as well as thermal continuum emission from interstellar dust particles in those same clouds (Heiles et al. 1993; Lazarian 2007; Hoang & Lazarian 2008; Matthews et al. 2009; Crutcher 2012). Aspherical dust particles irradiated by starlight are charged up by the photoelectric effect, as well as spun up as a result of radiative torques (RATs; e.g., Draine & Weingartner 1996, 1997; Lazarian & Hoang 2019). These spinning particles are aligned with their...
The Perseus molecular cloud, whose distance is about 300 pc from the Sun (Ortiz-León et al. 2018; Zucker et al. 2018; Pezzuto et al. 2021), is one of the most active star-forming molecular clouds in the solar vicinity (Bally et al. 2008). This cloud is associated with a single HI shell along with the Taurus, Auriga, and California molecular clouds. It has been suggested that this HI shell may have been formed by the interstellar bubble around the Perseus OB2 association (Bally et al. 2008; Lim et al. 2013; Shimajiri et al. 2019).

Doi et al. (2020) revealed that the active star-forming region NGC 1333 in the Perseus molecular cloud shows a complex B-field structure at spatial scales <1 pc. In their analysis, the small scale variation of the B-field is well explained if the B-field is generally perpendicular to the local dense ISM filaments. Fluctuations in the B-field structure at small spatial scales in the Perseus molecular cloud are also found by optical polarimetry (Goodman et al. 1990; Figure 1). The observed polarization angles indicate that POS orientations of the B-field ($\theta_{\text{star}}$) show two distinct populations. One population has a peak at $\theta_{\text{star}} \sim -40^\circ$ and the other population has a broader peak in position angles at $\theta_{\text{star}} \sim +70^\circ$. The two populations of vectors show no spatial segregation across the Perseus cloud complex (Goodman et al. 1990; see Figure 1).

It is not yet known whether these bimodal $\theta_{\text{star}}$ values represent the local variation of B-field orientations, differences in the characteristics of the dust particles, or whether that is caused by the superposition of multiple ISM components along the line of sight (LOS; Goodman et al. 1990; Matthews & Wilson 2002; Ridge et al. 2006a; Gu & Li 2019). In this paper, we combine optical polarimetry data with Gaia measurements of stellar distances, to determine the multi-layer distribution of the B-field in the direction of the Perseus molecular cloud. With this analysis, we aim to reveal the cause of the bimodal B-field structure observed in the Perseus molecular cloud region, which we find due to a contribution of the foreground Taurus molecular cloud. This paper is organized as follows. In Section 2, we describe the data used for our analysis. In Section 3, we analyze the stellar distances of optical polarimetry and identify contributions from the Perseus and foreground Taurus molecular clouds. In Section 4, we discuss the relationship between the HI
shell, which is thought to be associated with the Perseus-Taurus molecular cloud, and the B-field distribution we have identified. We also discuss the alignment between θ_{star} and the Planck-observed B-field orientation (θ_{planck}), which gives information on small-scale B-field structure below Planck’s beam size. In Section 5, we summarize the results.

2. Data

2.1. Optical and Near-infrared Stellar Polarimetry

We use optical polarimetry of 88 sources in the direction of the Perseus molecular cloud observed by Goodman et al. (1990) (Figure 1). The passband of the observations were centered at 762.5 nm with a bandwidth of 245 nm.

We also use NIR polarimetry data taken toward NGC 1333 in the Perseus molecular cloud, as shown in the inset of Figure 1. We use K-band polarimetry by Tamura et al. (1988), (14 sources) and R- and J-band polarimetry by Alves et al. (2011) (33 sources). The NIR θ_{star} are mainly distributed from θ_{star} ~ −90° to θ_{star} ~ −40°.

2.2. Planck Submillimeter Polarimetry

We estimate the B-field orientation measured in submillimeter dust emission by using Planck data at 353 GHz (Planck Collaboration et al. 2000). We use HFI_SkyMap_353-psb_2048_R3.01_full.fits taken from the Planck Legacy Archive, https://pla.esac.esa.int/. In our analysis, we set the spatial resolution of the Planck polarimetric data as a 10′ FWHM Gaussian to achieve good signal-to-noise ratios.

2.3. Gaia DR2 Photometry and Trigonometric Distances

We estimate the stellar distances by using Gaia astrometry data (DR2; Gaia Collaboration et al. 2016, 2018), and use SIMBAD (Wenger et al. 2000) positions to cross-match the stars in the Gaia catalog. We set a search radius of 5″ and take the star at the closest position for R-band and J-band data by Alves et al. (2011). The identified stars show M_G = 14–20 mag, and have good correspondence with the J-band magnitude tabulated by Alves et al. (2011).

For relatively old data sets by Goodman et al. (1990) and Tamura et al. (1988), we set a relatively large search radius of 30″ and take the brightest star in the searched region, which gives a good cross-match of the cataloged stars as follows. We find that the stars observed by Goodman et al. (1990) show G-band magnitude in the Gaia catalog between M_G = 7–15 mag. We exclude three stars that show M_G = 17–21 mag from the following analysis for their possible misidentifications. The stars observed by Tamura et al. (1988) show M_G = 10–18 mag. We exclude one star that shows M_G = 20 mag from the following analysis because of its non-reliable distance estimation (negative parallax).

The Gaia parallax in DR2 is known to have a systematic bias of −0.03 mas (see Bauer-Jones 2015; Arenou et al. 2018; Bauer-Jones et al. 2018; Lindgren et al. 2018; López-Corredoira & Sylos Labini 2019). This bias is negligible in our distance evaluation, as the stellar distances in our analysis are less than 1 kpc and thus their parallaxes are greater than 1 mas. Thus, we did not correct the bias, and estimate the distances of each star by d = 1000/π (pc).

The renormalised unit weight error (RUWE) is a parameter that is expected to be around 1.0 for sources where the single-star model provides a good fit to the astrometric observations. A value significantly greater than 1.0 (say, >1.4) could indicate that the source is non-single or otherwise problematic for the astrometric solution (see the Gaia data release documentation21). We estimate the RUWE for each source following the formulation described in the document “Re-normalizing the astrometric chi-square in Gaia DR2”22 and use the data only if whose RUWE ≤ 1.4.

As a result, we estimate the distances of 111 sources, including 70 sources from Goodman et al. (1990), 20 sources (R-band) and 15 sources (J-band) from Alves et al. (2011), and 6 sources from Tamura et al. (1988). We summarize the identified data in Table 5 in Appendix.

3. Results

3.1. Distance to the Clouds that Produce Polarization

Figure 1 shows the spatial distribution of the polarimetry data in our analysis with the inferred B-field morphology from Planck. The polarization position angles, θ_{star}, show a bimodal distribution, with concentrations at θ_{star} ~ +70° and θ_{star} ~ −40° (measured from North to East). Goodman et al. (1990) found that the two populations in θ_{star} also have distinct polarization fractions (P_{star}). We display the relationship between the observed θ_{star} and P_{star} in Figure 2. The population of θ_{star} ~ −40° show relatively larger P_{star} ≥ 1%, while the other population that has θ_{star} ~ +70° show relatively smaller P_{star} ≤ 1%.

In Figure 3, we display the θ_{star} and P_{star} dependences as a function of the estimated stellar distances. As seen in the figure, there is a clear jump in both distributions at a distance of about 300 pc, which is the distance to the Perseus molecular cloud. In addition to that, another jump is noticeable at a distance of about 150 pc. Hereafter, we call the polarmetry data whose stellar distances d ≥ 300 pc as Group 1, those with 150 < d < 300 pc as Group 2, and those with d ≤ 150 pc as Group 3, respectively. We summarize θ_{star} and P_{star} values of each group in Table 1.

Figure 3 shows that θ_{star} and P_{star} are both consistent within their own distance group. That is, the stars in Group 1 and the stars in Group 2 are tracing the polarization from ISM clouds located at distances of 300 pc and 150 pc, respectively. In particular, the consistency of P_{star} indicates that the ISM between and behind the two clouds does not significantly contribute to stellar polarization. Group 3 can be thought of as foreground stars with little interstellar extinction. We note that these stars have very high uncertainties in their polarization measurements due to having very low polarization fractions.

To quantitatively estimate the distance of the two ISM clouds that cause polarization, we perform a breakpoint analysis on θ_{star} and P_{star} distributions as a function of d, as shown in Figure 3. We assume that θ_{star} and P_{star} are constant as a function of d, which corresponds to the assumption that the observed polarization is caused by 2D sheet(s) of ISM at specific distance(s). In addition, we assume the θ_{star} and P_{star} distributions have a certain number of step-wise changes (i.e., breakpoints), which correspond to the positions of the 2D sheets. We perform least-squares fits to the data and make most likelihood estimations (MLE) of the positions of breakpoints.

We then repeat the fit with different number of breakpoints, and compare the goodness-of-fit values based on the Bayesian

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21 https://gea.esac.esa.int/archive/documentation/GDR2/
22 https://www.cosmos.esa.int/web/gaia/public-dpac-documents
We perform the breakpoint analysis for each distance dependence of $\theta$ and $P$ shown in Figure 3 by using the R library “strucchange” (Zeileis et al. 2002, 2003). For $\theta$ distribution analysis, we combine optical and NIR polarimetry data as shown in Figure 3 and use the shortest wave band data if multiple wave band data are available for a single star. On the other hand, we use only optical polarimetry data to analyze $P$ distribution because different wavelengths give different polarization fractions. We used $P$’s logarithm values in our analysis to detect breakpoints of widely different $P$ values (see Figure 3) with comparable sensitivity to each other.

The estimated distances of the breakpoints are shown in Figure 3 and Table 2. The breakpoint analysis shows that there are two breakpoints in both $\theta$ and $P$ distributions. The estimated distances are $150^{+139}_{-34}$ pc and $303^{+12}_{-7}$ pc for $\theta$, and $150^{+136}_{-3}$ pc and $295^{+22}_{-6}$ pc for $P$, respectively. Here we show the MLE positions and their 95% confidence intervals. Although the breakpoints in $P$ have larger errors compared to that in $\theta$ due to smaller jumps in $P$ values, the estimated distances are fully compatible between $\theta$ and $P$.

The distance of the breakpoint at 300 pc is consistent with the distance to the Perseus molecular cloud (Ortiz-León et al. 2018; Zucker et al. 2018; Pezzuto et al. 2021). Thus, we conclude that the polarization of Group 1 traces the B-field of the Perseus molecular cloud. The distance of another breakpoint at 150 pc is thought to indicate the distance to the foreground ISM cloud that causes the polarization of Group 2. This 150 pc foreground ISM also contributes to depolarizing Group 1. We will discuss this depolarization effect in Section 3.4. Group 3 are the foreground stars that show no clear indication of interstellar extinction.

3.2. Estimation of Cloud Distances Based on Photometry and Gaia Distances

In the previous section (Section 3.1), we estimated the distances of the breakpoints found in polarimetric data. The accuracy of estimation is limited to a few tens of parsecs...
because of the small number of data points. In this section, we perform a breakpoint analysis using all the available stellar photometric data in the Perseus molecular cloud direction to make a more accurate estimation of the distances to the breakpoints, including the foreground ISM. We then compare our result with other existing estimates of cloud distances in this direction to demonstrate the reliability of our method for measuring dust clouds’ distance.

We use G-band extinction ($A_G$) values cataloged in Gaia DR2 with $d \leq 1$ kpc and RUWE $\leq 1.4$, and fit these values as a function of distances obtained from Gaia parallax. The spatial distribution of the stellar data used in this analysis is shown in Figure 4. We note the paucity of stars in the direction of the dense molecular cloud. This is due to the larger extinction in the visible G band compared with the NIR bands.

Zucker et al. (2018) combined Gaia distance and NIR photometry to obtain the distance of each velocity component of the $^{12}$CO (1 − 0) line emission for each cloud core in the Perseus molecular cloud. We perform breakpoint analyses for similar spatial directions and compare the result with their estimation. Since the exact spatial region analyzed in Zucker et al. (2018) is not indicated in the literature, we estimate the breakpoints at 1° diameter regions centered at each molecular cloud core. The regions are shown as red circles in Figure 4.

We show the comparison of the results of our breakpoint analysis with the estimation by Zucker et al. (2018) in Figure 5 and Table 3. Our results are in reasonable agreement with those of Zucker et al. (2018) for each component of the Perseus cloud at a distance of about 300 pc. The estimated distances show a gradual increase from west to east as pointed out by Zucker et al. (2018).
the CO molecular clouds are shown above the regions where we estimate the breakpoint distances and compare them with the CO molecular cloud distances estimated by Zucker et al. (2019). Names of the CO molecular clouds are shown above the figure. See Section 3.2 and Figure 5 for the details of the comparison.

Figure 6(a) shows the results of our breakpoint analysis. The spatial resolution of this analysis is set as 55'2. The estimated cloud distances are concentrated at 150 pc and 300 pc (Figure 6(a)).

Figures 6(b) and (c) show the results by Lallement et al. (2019) and Leike & Enßlin (2019), respectively. Both two dust maps successfully detect the foreground cloud in addition to the Perseus cloud. Lallement et al. (2019, Figure 6(b)) combine 2MASS photometric data with Gaia DR2. Their map has limited LOS resolution of 50 pc and thus the estimated extinction for the Perseus cloud is smoothed out, resulting in relatively lower extinction per unit length value (~0.01 mag pc⁻¹) compared to (Leike & Enßlin 2019, Figure 6(c)). Lallement et al. (2019) indicated plans to improve the LOS resolution as the Gaia data is updated.

Leike & Enßlin (2019) and Figure 6(c) (also see Leike et al. 2020) used the Gaia DR2 $A_G$ values as photometric data to create a 3D dust map of the solar vicinity ($d \lesssim 300$ pc). They achieved higher resolution in LOS comparing to the map by Lallement et al. (2019) that used NIR photometric data (Figure 6(b)). NIR photometry is effective for tracing dense molecular clouds’ interiors but has limited sensitivity for tracing faint clouds with a high spatial resolution. On the other hand, the disadvantage of tracing the shape of the dust cloud using only photometry of visible wave bands is also apparent; in their analysis shown in Figure 6(c), the 300 pc Perseus molecular cloud cannot be correctly detected due to saturation of the $A_G$ value and is split into two distances before and after the cloud.

Our results shown in Figure 6(a) are based on the simple 2D sheet assumption and have limited spatial resolution of about 1°, but the use of the $A_G$ value achieves a good sensitivity to faint clouds as well as the correct determination of the distances of dense molecular clouds.

According to the discussions above, we judge that our method is a simple and effective one for measuring dust clouds. Using $G$-band photometry, we can obtain the distance to both faint and dense clouds stably and accurately. Our results described in Section 3.1 (Figure 3) are thus consistent that the stellar polarization in the Perseus molecular cloud’s direction originates in two isolated clouds at 150 pc and 300 pc, which are both detected by Lallement et al. (2019) and Leike & Enßlin (2019).

3.3. Spatial Distribution of Individual Clouds

Figure 7 shows the spatial distribution of the dust cloud at 150 pc and 300 pc by Leike & Enßlin (2019) as contours. To avoid the effect of LOS splitting of the dense molecular cloud, we show the spatial distribution of the integrated $A_G$ magnitude in the 100–200 pc range for the 150 pc component and in the 250–350 pc range for the 300 pc component, respectively. In addition to the Perseus cloud (the top panel of Figure 7), we also show the Taurus-Perseus molecular cloud complex in the bottom panel of Figure 7. As is evident in Figure 7, the 150 pc foreground cloud lying in front of the Perseus molecular cloud corresponds to the outer edge of the Taurus molecular cloud at a distance of ~140 pc (Yan et al. 2019; Zucker et al. 2019; Roccatagliata et al. 2020), as was proposed by Ungerechts & Thaddeus (1987) and Cernis (1990). The estimated extinction of the foreground cloud based on Leike & Enßlin (2019) is $A_G^{150\text{pc}} = 0.1–0.9$ mag.

We overlay the $B$-field orientation measured by Planck ($\theta_{\text{Planck}}$) in Figure 7 as black line segments. $\theta_{\text{Planck}}$ toward the Perseus cloud is generally aligned to the northwest-southeast direction. The circular mean and the circular standard deviation are $\theta_{\text{Planck}} = -56^\circ \pm 25^\circ$ if we estimate them in the region where the 300 pc dust cloud component $A_G^{300\text{pc}} > 0.6$ mag. This $\theta_{\text{Planck}}$ is consistent with the optical $\theta_{\text{star}}$ of Group 1 ($-37^\circ/35^\circ/2$). Outside the Perseus molecular cloud but on the foreground component, we note a significant change in the $B$-field orientation. If we estimate $\theta_{\text{Planck}}$ on the foreground cloud whose $A_G^{150\text{pc}} > 0.2$ mag, $A_G^{300\text{pc}} < 0.6$ mag, and R.A. $<4^h00^m$, the position angle is $\theta_{\text{Planck}} = -89^\circ \pm 19^\circ$, which is considerably different from $\theta_{\text{Planck}}$ on the Perseus molecular cloud and is consistent with the $\theta_{\text{star}}$ of Group 2 ($+66^\circ8^\circ \pm 19^\circ$) within the range of errors.

As a result, we conclude that there are two $B$-field components observed in the Perseus molecular cloud’s direction: one is the Perseus molecular cloud’s $B$-field, and the other is that of a tenuous cloud at the outer edge of the Taurus molecular cloud with $A_G < 1$ mag.

3.4. Polarization of the Two Clouds

The two-component $B$-field of Perseus and Taurus clouds, described in the previous section, is traced by Group 1 ($d > 300$ pc) and Group 2 ($150 < d < 300$ pc) stellar polarization data.
Figure 5. Estimated distances of major star-forming regions across the Perseus molecular cloud. Results of our breakpoint analysis (“this work” in the figure) are compared with the CO distances by Zucker et al. (2018) (see also Table 3). Our breakpoint analysis identifies multiple clouds in each region (Table 3, 4th–6th columns). On the other hand, Zucker et al. (2018) identifies distances for each velocity component of the $^{12}$CO ($1-0$) emission line (Table 3, 7th–13th columns). Therefore, the clouds identified by this work and Zucker et al. (2018) do not necessarily have a one-to-one correspondence. For simplicity, we show the closest pair of clouds by Zucker et al. (2018) in the same region for each cloud identified by the breakpoint analysis. Similarly, for each cloud by Zucker et al. (2018), the closest cloud in the same region by the breakpoint analysis is shown as a pair. Therefore, note that the same cloud may be paired with two different clouds and shown twice in the figure.

Table 3

| Cloud Name | R.A. (deg) | Decl. (deg) | This Work (pc) | Zucker et al. (2018) a (pc) |
|------------|------------|-------------|----------------|---------------------------|
| L1451      | 51.0       | 30.5        | 146±7 10       | 282±7 0                   |
| L1448      | 51.2       | 30.9        | 154±6 25       | 277±7 3                   |
| NGC 1333   | 52.2       | 31.2        | 176±6 38       | 264±6 9                   |
| B1         | 53.4       | 31.1        | 142±4 30       | 213±4 1                   |
| IC 348     | 55.8       | 31.8        | 131±5 32       | 202±5 1                   |
| B5         | 56.9       | 32.9        | 156±10 15      | 302±5 8                   |

Note.

a Estimated distances to each velocity component of the CO molecular line emission for each cloud (Zucker et al. 2018) are shown. The leftmost (closest) components of each cloud are foreground components.
Group 2 traces only the Taurus cloud, while Group 1 sees through both Perseus and Taurus clouds. Here we estimate the Perseus molecular cloud’s $B$-field by removing the Taurus contribution from Group 1. The observed polarization fraction is $\lesssim 10\%$ (Figure 3 and Table 1). In such a low polarization condition, the relative Stokes parameters $q (= Q/I)$ and $u (= U/I)$ in the polarized flux can be approximated as additive (e.g., Panopoulou et al. 2019b and the references therein). In other words, we can separate the contribution to the polarization from individual clouds as follows.

$$q_{\text{Group1}} = q_{\text{Taurus}} + q_{\text{Perseus}},$$

$$q_{\text{Group2}} = q_{\text{Taurus}},$$

where $q_{\text{Group1}}$ and $q_{\text{Group2}}$ are the relative Stokes $q$ parameter observed for Group 1 and Group 2 stars, and $q_{\text{Taurus}}$ and $q_{\text{Perseus}}$ are the relative Stokes $q$ parameter originated in Taurus and Perseus clouds, respectively. These formulas also hold for the relative Stokes $u$ parameter. We estimate $q_{\star}$ and $u_{\star}$ values of Group 1 and Group 2 from the observed $\theta_{\star}$ and $P_{\star}$ as follows.

$$q_{\star} = P_{\star} \times \cos(2 \cdot \theta_{\star}),$$

$$u_{\star} = P_{\star} \times \sin(2 \cdot \theta_{\star}).$$

The estimated $q_{\star}$ and $u_{\star}$ are shown in Figure 8(a).

The $q$ and $u$ values of Group 1 show a significant scatter, reflecting the local variation in $\theta_{\star}$ and $P_{\star}$ of Group 1. On the other hand, the data of Group 2, which represents the $q$ and $u$ values of the Taurus cloud, show a small variation. This is because $\theta_{\star}$ and $P_{\star}$ of Group 2 have a small spatial variation, and the value of $P_{\star}$ is also small (see Table 1).

Since $q$ and $u$ are additive, the observed values of $q$ and $u$ in Group 1 can be expressed as a vector sum of the contributions from Perseus and Taurus clouds on the $q$–$u$ plane. This

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Figure 6. Comparison of the distributions of the breakpoints distances in the Perseus molecular cloud direction ($157^\circ < l < 161^\circ$, $-23^\circ < b < -16^\circ$) with existing 3D dust maps as a function of the distance. Vertical axes are for the $G$-band extinction ($A_G$) per each detected cloudlet (i.e., breakpoint) for panel (a), and $A_G$ per pc for panels (b) and (c).
the Perseus main cloud is dominant compared to that of the foreground Taurus cloud’s outskirt (see Figure 6). As a result, the Taurus contribution to the Group 1 polarization does not significantly change the Perseus’ \( q-u \) vector direction (Figure 8(b)). Thus, we conclude the following:

\[
\theta_{\text{Perseus}} \simeq \theta_{\text{Group1}}, \\
\theta_{\text{Taurus}} = \theta_{\text{Group2}}.
\]

On the other hand, we estimate that \( P_{\text{Perseus}} \) is slightly larger than \( P_{\text{Group1}} \) due to the depolarization by the foreground Taurus cloud. We estimate \( \theta_{\text{Perseus}} \) and \( \theta_{\text{Taurus}} \) by subtracting the averaged Group 2 \( q-u \) vector from the observed Group 1 \( q-u \) vectors, as shown in Figure 8(b). The results are shown in Table 4.

Figure 9 shows \( P_{\text{Perseus}} \) and \( P_{\text{Taurus}} \) as a function of \( A_G \) to investigate individual clouds’ polarization efficiency \( (P \_\text{stat}/A_G) \). We assume that the Taurus cloud’s \( A_G \) values are equal to the Group 2 data. For the Perseus cloud, we estimate \( A_G \) by subtracting that of 150 pc cloud component estimated by Leike & Enßlin (2019) and Figure 7 at each position of the stars from the observed Group 1 \( A_G \) values. Note that the maximum observed \( A_G \) value is 3 mag (also see Figure 13 and the discussion in Sections 4.2 and 4.3), indicating that the stellar extinction data are biased to regions in the cloud where the extinction is smaller (\( A_G < 3 \) mag).

In Figure 9, we also show the observed maximum polarization efficiency taken from the literature \( (P/E (B - V) = 13\% \); Panopoulou et al. 2019a; Planck Collaboration et al. 2000). The polarization efficiency of Taurus and Perseus corresponds to less than \(-50\% \) of the maximum efficiency. We do not find a significant difference between the polarization efficiencies of Taurus and Perseus clouds.

4. Discussion

4.1. B-field Orientation and the Per OB2 Bubble

In Section 3.3, we identified that the 150 pc foreground cloud lying in front of the Perseus molecular cloud is the outer edge of the Taurus molecular cloud. Both Taurus and Perseus molecular clouds are thought to be on a common large Hi shell’s outer edge (Sancisi 1974; Sun et al. 2006; Shimajiri et al. 2019). In Figure 6, we find a low-extinction region between these two clouds. In the following, we estimate the spatial extent of this low-extinction region.

Figure 10 shows the 3D distribution of the dust cloud in the region containing Taurus and Perseus. We estimate the 3D shape of the dust shell by using the cloud positions determined by our breakpoint analysis. We assume the shell’s profile as a simple ellipsoid and perform a least-square fit of the shell to the cloud positions weighted by their extinction (mag/cloud). The estimated size and position of the shell are shown in Figure 11.

As shown in the figure, we can identify a low-density dust cavity surrounded by the dust shell. The estimated diameters in the heliocentric galactic Cartesian coordinates (X, Y, and Z directions; see Figure 10 for the definition of X, Y, and Z) are \( D_x \approx 156 \) pc, \( D_y \approx 110 \) pc, and \( D_z \approx 105 \) pc, centering at \( 370 \pm 220 \) pc, \( Y \approx 38 \) pc, and \( Z \approx -80 \) pc. The ellipsoid’s estimated shape is also shown in Figure 10, and the outline of the ellipsoid projected on the POS is shown in Figure 7 (bottom panel). The Taurus molecular cloud is located in front of this cavity, and the Perseus molecular cloud is located behind it. Thus, we conclude that the two-component B-fields observed in...
the Perseus cloud’s direction at distances of 150 pc and 300 pc show the B-field structure in front of and behind the dust cavity, respectively.

The HI shell and dust cavity are thought to be formed by the Per OB2 association. The velocity field that is consistent with the assumed expanding motion of the shell was found for the Perseus molecular cloud in the HI (Sancisi 1974) and CO (Sun et al. 2006; Ridge et al. 2006b) line emissions (see, e.g., Figure 10 of Sun et al. 2006). Tahani et al. (2018) found that the LOS B-field directions are different from each other in the north and south of the east–west extending Perseus molecular cloud. This LOS B-field is consistent with a scenario where the environment has impacted and influenced the field lines to form a bow-shaped magnetic field morphology as explored in Heiles (1997) and (Tahani et al. 2019, also see Inoue et al. 2018). $\theta_{\text{star}}$ of the Perseus cloud B-field component is $-30.0\pm25.2$° (Section 3.4 and Table 4). In the galactic coordinates, $\theta_{\text{star}}^{\text{GAL}}$ (measured from Galactic North to Galactic East) of the Perseus cloud B-field is $-68.2\pm24.9$. This $\theta_{\text{star}}^{\text{GAL}}$ is nearly parallel to the galactic plane (see Figure 3, top panel), i.e., it is consistent with the global B-field component of the galaxy (see, e.g., Jansson & Farrar 2012, Figure 9). This $\theta_{\text{star}}^{\text{GAL}}$ is, therefore, in accordance with the formation scenario of the Perseus molecular cloud described above. The impact of feedback on the B-fields is explored on a forthcoming paper (Tahani et al., in prep).

On the other hand, the orientation of the Taurus B-field is close to perpendicular to the galactic plane ($\theta_{\text{star}}^{\text{GAL}} = 28.7\pm19.8$°; Figure 3, top panel). It is difficult to form a B-field structure close to perpendicular to the galactic plane (i.e., perpendicular to the global B-field of the galaxy) if the ISM is compressed simply along the LOS. Thus, the observed $\theta_{\text{star}}$ in front of and behind the dust cavity is not compatible with the simple expansion of HI bubble in a uniform B-field.

As shown in the discussion in this section, thanks to the advent of Gaia data, we can now isolate the B-fields associated with each of the multiple clouds superimposed along the LOS and map them to the 3D structure of the ISM (see also Panopoulou et al. 2019b, and the references therein). This isolation of the B-fields is important in studying the B-field properties of individual clouds, e.g., applying the DCF method (Davis 1951; Chandrasekhar & Fermi 1953) to estimate the B-field strength.

### Table 4

| Cloud     | $\theta_{\text{star}}$ (deg) | $P_{\text{star}}$ (%) | $A_{\text{G}}$ (mag) | $P_{\text{star}}/A_{\text{G}}$ (%)/(mag) |
|-----------|-----------------------------|------------------------|-----------------------|------------------------------------------|
| Taurus    | $+66.8 \pm 19.1$           | 0.8 ± 0.6              | 0.32 ± 0.21           | 1.5 ± 0.3                                |
| Perseus   | $-30.0 \pm 25.2$           | 2.4 ± 1.8              | 1.61 ± 0.58           | 1.5 ± 0.2                                |

In Figure 1, we showed the spatial distribution of $\theta_{\text{star}}$ and $\theta_{\text{Planck}}$. We note that the Group 1 $\theta_{\text{star}}$ (d > 300 pc; red points in Figure 1) has a good one-to-one correspondence with $\theta_{\text{Planck}}$ in the same position, despite their spatial variations. Figure 12 shows the offset angle between $\theta_{\text{star}}$ and $\theta_{\text{Planck}}$ as a function of stellar distance.

For stars closer than 300 pc, the offset angle is $\theta_{\text{star}} - \theta_{\text{Planck}} = -71\pm45$° and shows large variation, while for stars farther than 300 pc, the offset angle is $\theta_{\text{star}} - \theta_{\text{Planck}} = 2\pm28$°. $\theta_{\text{Planck}}$ traces the B-field approximately in proportion to the column density along the LOS. Thus, $\theta_{\text{Planck}}$ mainly traces the Perseus molecular cloud, with an additional contribution from the foreground cloud (see Figure 6). As discussed in Section 3.4, this also applies to $\theta_{\text{star}}$ of Group 1. As a result, $\theta_{\text{Planck}}$ agrees well with the Group 1 $\theta_{\text{star}}$ as they trace...
the similar ISM on the LOS. On the other hand, \( \theta_{\text{star}} \) of Group 2 and Group 3 has no contribution from the Perseus cloud, and the foreground contribution traced by them is much smaller than that of the Perseus cloud in the background. Therefore, \( \theta_{\text{star}} \) of Group 2 and Group 3 does not correlate with \( \theta_{\text{Planck}} \). Thus, we conclude that \( \theta_{\text{star}} \) and \( \theta_{\text{Planck}} \) observations of the

**Figure 9.** \( P_{\text{star}} \) of Perseus and Taurus clouds as a function of \( A_G \). See text for the estimation of \( P_{\text{star}} \) and \( A_G \) of individual clouds. The dashed lines show the observed maximum polarization efficiency \( (P/E(B - V) = 13\% ; \text{Panopoulou et al. 2019a; Planck Collaboration et al. 2000}) \) and its 50\% slope. We assume \( A_G / A_V = 0.789 \) and \( A_V / E(B - V) = 3.16 \) (Wang & Chen 2019) to convert \( E(B - V) \) to \( A_G \).

**Figure 10.** The 3D distribution of dust clouds in the Taurus-Perseus region. Coordinates are the heliocentric galactic Cartesian coordinates; the X-axis points to the galactic center, the Y-axis points to the direction of galactic rotation (galactic plane \( l = 90^\circ \)), and the Z-axis points to the galactic north pole. Points are the cloud positions determined by our breakpoint analysis, and the color scale is the distribution of dust clouds estimated by Leike & Enßlin (2019), available for the regions \( X \geq -300 \) pc. The distribution from parallel to the galactic plane at \( Z = 0 \) pc to \( Z = -160 \) pc at every 20 pc is shown. Yellow dashed ellipses show the cross-sectional profiles of the dust cavity (see Section 4.1).
Perseus molecular cloud’s direction with stellar distances $d > 300$ pc are in good agreement with each other, despite the fact that their spatial resolutions are largely different from each other. The spatial resolution of $\theta_{\text{Planck}}$ is 10', which corresponds to $\sim 1$ pc at 300 pc from the Sun. On the other hand, the spatial resolution of $\theta_{\text{star}}$ is the size of stellar photospheres, which is much smaller than the Planck's beam size.

The good one-to-one correspondence between $\theta_{\text{star}}$ and $\theta_{\text{Planck}}$ was first pointed out by Planck Collaboration et al. (2015b) (see also Gu & Li 2019). Soler et al. (2016) further analyzed the $\theta_{\text{star}}$–$\theta_{\text{Planck}}$ correlation and investigated possible small-scale structures of the B-field inside the Planck beam. They concluded that the B-field inside the Planck beam is uniform or randomly fluctuated around the mean $\theta$, because $\theta_{\text{Planck}}$ agrees with $\theta_{\text{star}}$. Our observed good correlation between $\theta_{\text{Planck}}$ and $\theta_{\text{star}}$ supports their conclusion.

We show the offset angle between $\theta_{\text{star}}$ and $\theta_{\text{Planck}}$ as a function of the stellar extinction in Figure 13. The data show good agreement (angle differences consistent with zero) with no clear dependence on column density. The data shown here suggest that the small scale B-field is smooth in the column density range up to $A_G \sim 3$ mag or hydrogen column density $N_H \sim 10^{22}$ (cm$^{-2}$).

In addition, Figure 12 suggests that the correlation between $\theta_{\text{Planck}}$ and $\theta_{\text{star}}$ does not change with the stellar distance beyond 300 pc. As shown in Section 3.1 and Figure 3, $\theta_{\text{star}}$ and $P_{\text{star}}$ show no clear variation as a function of the stellar distance. The good correlation between $\theta_{\text{star}}$ and $\theta_{\text{Planck}}$ thus indicate that the ISM between and behind the clouds does not significantly contribute to polarization in either emission ($\theta_{\text{Planck}}$) or extinction ($\theta_{\text{star}}$). In other words, the polarization is produced only in dense clouds along the LOS.

4.3. Small-scale B-field in Low- and High-column Density Regions

Doi et al. (2020) performed submillimeter polarimetry observations of NGC 1333, a dense star-forming region in the Perseus molecular cloud. They observed the region with POL-2 on JCMT, and revealed the B-field orientation ($\theta_{\text{JCMT}}$) with a high spatial resolution of $\lesssim 0.02$ pc. The observed region has ISM column density $N_H \gtrsim 10^{23}$ (cm$^{-2}$; also see Figure 1). In contrast to the good agreement between $\theta_{\text{star}}$ and $\theta_{\text{Planck}}$ described in the previous section, $\theta_{\text{JCMT}}$ is not well correlated with $\theta_{\text{Planck}}$. Instead, $\theta_{\text{JCMT}}$ shows significantly more complex structure on $< 0.5$ pc scales. Doi et al. (2020) found that the small-scale B-field appears to be twisted perpendicular to the
gravitationally supercritical massive filaments, most probably due to the dense filaments’ formation.

Hence, the small scale (<1 pc) B-field appears to be highly complicated for the regions with \( N_\text{H} \gtrsim 10^{23} \text{ cm}^{-2} \) but smooth for the regions with \( N_\text{H} < 10^{22} \text{ cm}^{-2} \). It is unknown about the small-scale B-field structure for the regions with \( N_\text{H} = 10^{22} - 10^{23} \text{ cm}^{-2} \). This is because optical and NIR stellar polarimetry cannot trace \( N_\text{H} \gtrsim 10^{22} \text{ cm}^{-2} \) ISM, while ground-based and airborne submillimeter telescopes currently lack sensitivity to trace \( N_\text{H} < 10^{24} \text{ cm}^{-2} \) ISM. But as described below, observations of the LOS B-field strength and Planck polarimetry with the lower spatial resolution hint at the increasing complexity of small-scale B-field structure at \( N_\text{H} > 10^{22} \text{ cm}^{-2} \).

Crutcher (2012) showed that the LOS B-field strength measured by Zeeman splitting measurements show a general increase with an increasing \( N_\text{H} \) when \( N_\text{H} > 10^{22} \text{ cm}^{-2} \). In such a high-column density region, Planck Collaboration et al. (2015a) observed a sharp drop in \( P_{\text{Planck}} \) where \( N_\text{H} \gtrsim 1.5 \times 10^{22} \text{ cm}^{-2} \). They also reported an increase of the polarization angle dispersion at the same column density range. Planck Collaboration et al. (2016) and Soler (2019) found that the relative orientation of the Planck-observed B-fields to the long axes of dense filaments changes systematically from being parallel to perpendicular at \( N_\text{H} \approx 5 \times 10^{21} \text{ cm}^{-2} \), which is consistent with the result reported by Doi et al. (2020).

Photometric observations also suggest that ISM clouds make a significant change in this column density range. Onishi et al. (1998) found recently formed protostars only in regions with \( N_\text{H} > 8 \times 10^{21} \text{ cm}^{-2} \) in the Taurus molecular cloud. Johnstone et al. (2004) and Kirk et al. (2006) found no obvious substructures below an \( N_\text{H} \sim 10^{22} \text{ cm}^{-2} \) in their submillimeter continuum observations of the Ophiuchus cloud and the Perseus cloud, respectively. Many authors have pointed out that there is a fiducial threshold of \( N_\text{H} \approx 10^{22} \text{ cm}^{-2} \) for the star formation (e.g., Lada et al. 2010, 2012; Heiderman et al. 2010; Evans et al. 2014; Könyves et al. 2015; Marsh et al. 2016; Zhang et al. 2019), though some counterexamples are reported by, e.g., Di Francesco et al. (2020) (lower threshold value) and Pokhrel et al. (2020) (no threshold value). Interestingly, the critical line mass of ISM filaments (\( M_{\text{line,crit}} = 2\zeta^2 / G \approx 16 M_\odot \text{ pc}^{-1} \) for \( T_{\text{gas}} = 10 \text{ K} \); Stodolkiewicz 1963; Ostriker 1964; Inutsuka & Miyama 1997) is consistent with this threshold \( N_\text{H} \) value if we adopt the typical 0.1 pc width of the filaments (Andrè et al. 2014).

These observations described above suggest that ISM clouds make a critical change above \( N_\text{H} \sim 10^{22} \text{ cm}^{-2} \). Suppose the small scale B-field becomes complex and the B-field strength increases at \( N_\text{H} > 10^{22} \text{ cm}^{-2} \). In that case, it could potentially show that the molecular clouds become gravitationally supercritical when \( N_\text{H} \gtrsim 10^{22} \text{ cm}^{-2} \), and thus the small scale structure in the molecular clouds are formed in this column density range. The B-field might be bent and distorted in the formation of gravitationally supercritical small scale structures or dense filaments. Therefore, the B-field structure may record these small-scale structures’ formation history. High spatial resolution (e.g., <15") interstellar B-field observations in this column density range, if achieved, could provide important information on the formation of cloud structure in the early stages of star formation.

Figure 12. The angle difference between the optical polarimetry (\( \theta_{\text{star}} \)) and the Planck-observed B-field (\( \theta_{\text{Planck}} \)) in the Perseus molecular cloud’s direction. The spatial resolution of the Planck observation is set as 10". The offset angle is shown as a function of stellar distances observed by Gaia. Note that the horizontal axis is a linear scale below 300 pc, but a logarithmic scale above 300 pc. The dotted lines at \( d = 150 \text{ pc} \) and 300 pc indicate the two breakpoints identified in \( \theta_{\text{star}} \) and \( P \) (Section 3.1), corresponding to the Taurus and Perseus clouds (Section 3.3).
5. Conclusions

We studied the optical polarimetry data in the Perseus molecular cloud’s direction together with the Gaia parallax distance of each star. We found that observed values of both polarization angles and fractions show a discrete jump at 150 pc and 300 pc and otherwise remain constant. Thus, the polarization is originated in the dust clouds at 150 pc and 300 pc. The ISM between and behind the clouds does not make a significant contribution to the polarization.

The dust cloud at 300 pc corresponds to the Perseus molecular cloud. We estimate the POS B-field orientation angle of the Perseus molecular cloud as $-30^\circ.0 \pm 25^\circ.2$. The Perseus cloud has the highest column density in LOS, and thus Planck observations of the dust continuum in this direction mainly trace this cloud. The optical polarization angles (stellar distances $d > 300$ pc) and the Planck-observed B-field orientations are therefore well aligned with each other, although their spatial resolutions are largely different.

The dust cloud at a distance of 150 pc is faint with $A_G < 1$ mag, and the POS B-field orientation angle is $+66^\circ.8 \pm 19^\circ.1$. We identified this cloud as the outer edge of the Taurus molecular cloud at the same distance.

The two dust clouds are at the front- and back-sides of a dust cavity, which corresponds to an HI bubble structure generally associated with the Per OB2 association. We estimate the size of the dust cavity as 100–160 pc. The observed two components of the POS B-field orientations show the B-field orientations in front of and behind the cavity, which are nearly perpendicular to one another.

Thanks to the advent of Gaia data, we can now isolate the B-fields associated with each of the multiple clouds superimposed along the LOS and map them to the 3D structure of the ISM. This process can be applied to other regions, and we hope such efforts provide an important step toward understanding the 3D B-field structure of the ISM.

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Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This work has made use of observations obtained with Planck (http://www.esa.int/Planck), an ESA science mission with instruments and contributions directly funded by ESA Member States, NASA, and Canada. This research has also made use of the SIMBAD database and of NASA’s Astrophysics Data System Bibliographic Services.

Facilities: Gaia, Planck.
Software: strucchange (Zeileis et al. 2002, 2003), astropy (Astropy Collaboration et al. 2013).

Appendix
Data List

We list the cross-matching results between stellar polarimetry data and the Gaia catalog in Table 5. See Section 2.3 for the cross-matching procedure.

| Ref. | No. | R.A. (ICRS) (deg) | Dec. (ICRS) (deg) | P (%) | δP (%) | θ (deg) | δθ (deg) |
|------|-----|------------------|------------------|-------|--------|--------|----------|
| 1    | 1   | 50.89583         | 30.54518         | 1.15  | 0.10   | 80     | 2        |
| 1    | 2   | 50.96720         | 30.58552         | 0.78  | 0.09   | 82     | 3        |
| 1    | 3   | 51.07634         | 30.26754         | 0.02  | 0.06   | -35    | 6        |
| 1    | 4   | 51.33642         | 30.06133         | 0.13  | 0.10   | -74    | 21       |
| 1    | 5   | 51.44488         | 30.74159         | 0.64  | 0.09   | 76     | 4        |
| 1    | 6   | 51.45880         | 30.93167         | 1.38  | 0.09   | -70    | 2        |
| 1    | 7   | 51.61334         | 30.15060         | 1.14  | 0.07   | 85     | 2        |
| 1    | 8   | 51.62439         | 30.78881         | 1.97  | 0.09   | -59    | 1        |
| 1    | 9   | 51.82006         | 30.03606         | 0.55  | 0.09   | 76     | 5        |
| 1    | 10  | 51.87204         | 30.72097         | 1.33  | 0.05   | -61    | 1        |

Gaia No.² | Distance (pc) | ΔDistance (pc) | \( A_G \) (mag) | Δ\( A_G \) (mag) | RUWE⁴ | Bad⁵ |
|-----------|---------------|----------------|-----------------|------------------|-------|------|
| 123890260094849536 | 292.1 | +5.7 | -5.5 | ... | ... | ... | 0.87 | 0 |
| 123891256527257088 | 290.2 | +5.4 | -5.3 | 0.3250 | +0.1290 | -0.1534 | 0.93 | 0 |
| 120877357716054528 | 115.8 | +0.9 | -0.8 | 0.1053 | +0.1098 | -0.0883 | 0.98 | 0 |
| 120858764801761152 | 125.1 | +0.8 | -0.8 | 0.2540 | +0.2108 | -0.2150 | 0.99 | 0 |
| 120987682540431744 | ... | ... | ... | ... | ... | ... | 1.07 | 1 |
| 123999730221048320 | 313.7 | +6.9 | -6.6 | ... | ... | ... | 0.98 | 0 |
| 120819186679044480 | 296.1 | +5.6 | -5.4 | 0.7603 | +0.4418 | -0.4440 | 1.03 | 0 |
| 120991672565773568 | 818.7 | +53.2 | -47.1 | 1.1480 | +0.6735 | -0.2385 | 1.11 | 0 |
| 120803686141726336 | 254.4 | +5.0 | -4.8 | ... | ... | ... | 0.95 | 0 |
| 120979406139173376 | 350.3 | +9.3 | -8.9 | 0.8060 | +0.1260 | -0.1941 | 1.09 | 0 |

Notes.
² Reference number. 1: Optical (Goodman et al. 1990, Table 3), 2: R-band (Alves et al. 2011, Table 5), 3: J-band (Alves et al. 2011, Table 5), 4: K-band (Tamura et al. 1988, Table 2).
³ Source number in each reference.
⁴ Gaia source ID in DR 2.
⁵ Bad flag. Bad = 1 indicates that the data entry is discarded from the analysis in this paper because of its large RUWE (>1.4), non-reliable Gaia parallax (NA or negative values), or erroneous identification (G magnitude >15 mag for data by Goodman et al. (1990)).

(This table is available in its entirety in machine-readable form.)
References

Alves, F. O., Acosta-Pulido, J. A., Girart, J. M., Franco, G. A. P., & López, R. 2011, 

Andersson, B.-G., Lazarian, A., & Villacroscia, J. E. 2015, ARA&A, 53, 501

André, P., Di Francesco, J., Ward-Thompson, D., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson, AZ: Univ. Arizona Press), 27

Arenou, F., Luri, X., Babusiaux, C., et al. 2018, A&A, 616, A17

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33

Bailer-Jones, C. A. L. 2015, PASP, 127, 994

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2016, A&A, 576, A104

Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2015a, A&A, 576, A104

Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2015b, A&A, 576, A106

Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, A&A, 586, A135

Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2020, A&A, 641, A12

Pokhrel, R., Gutermuth, R. A., Betti, S. K., et al. 2020, ApJ, 896, 60

Ridge, N. A., Di Francesco, J., Kirk, H., et al. 2006b, AJ, 131, 2921

Ridge, N. A., Schnee, S. L., Goodman, A. A., & Foster, J. B. 2006a, ApJ, 643, 932

Roccatagliata, V., Franceschini, E., Sacco, G. G., Rand ich, S., & Sicilia-Aguilar, A. 2020, A&A, 638, A85

Sancisi, R. 1974, in IAU Symp. 60, Galactic Radio Astronomy, ed. J. F. Kerr & S. C. Simonson (Dordrecht: D. Reidel), 115

Shimajiri, Y., André, P., Palmeirim, P., et al. 2020, A&A, 624, A16

Soler, J. D. 2019, A&A, 629, A96

Soler, J. D., Alves, F., Boulanger, F., et al. 2016, A&A, 596, A93

Stein, W. 1966, ApJ, 144, 318

Stodoláková, J. W. 1963, AcA, 13, 30

Sun, K., Kramer, C., Ossenkopf, V., et al. 2006, A&A, 451, 539

Tahani, M., Plume, R., Brown, J. C., & Kainulainen, J. 2018, A&A, 614, A100

Tahani, M., Plume, R., Brown, J. C., Soler, J. D., & Kainulainen, J. 2019, A&A, 632, A68

Tamura, M., Yamashita, T., Sato, S., Nagata, T., & Gatley, I. 1988, MNRAS, 231, 445

Ungerechts, H., & Thaddeus, P. 1987, ApJS, 63, 645

Wang, S., & Chen, X. 2019, ApJ, 877, 116

Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, A&AS, 143, 9

Yan, Q.-Z., Yang, J., Sun, Y., Su, Y., & Xu, Y. 2019, ApJ, 885, 19

Zari, E., Lombardi, M., Alves, J., Lada, C. J., & Bouy, H. 2016, A&A, 587, A106

Zeileis, A., Kleiber, C., Krämer, W., & Hornik, K. 2003, Comput. Stat. Data Anal., 44, 109

Zeileis, A., Leisch, F., Hornik, K., & Kleiber, C. 2002, J. Stat. Software, 7, 1

Zhang, M., Kainulainen, J., Mattern, M., Fang, M., & Henning, T. 2019, A&A, 622, A52

Zucker, C., Schlafly, E. F., Speagle, J. S., et al. 2018, ApJ, 869, 83

Zucker, C., Speagle, J. S., Schlafly, E. F., et al. 2019, ApJ, 879, 125