Multiwavelength stellar polarimetry
of the filamentary cloud IC5146. I.
Dust properties

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INVESTIGATE THE MAGNETIC STRUCTURE IN THE FILAMENTARY CLOUD IC5146 BY MULTI-WAVELENGTH POLARIMETRY

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ABSTRACT

Herschel Gould Belt Survey shows that the density profiles of the filamentary clouds favor the scenario that the filaments are generated by large scale turbulence (e.g. André et al. 2010; Arzoumanian et al. 2011). We present optical and near-infrared polarization observations toward IC5146, one of the targets in Gould Belt Survey, to investigate the role of magnetic field (B-field) in the cloud evolution. About 2000 background stars are detected in our observations over the $A_V < 20$ mag region. The observed B-field shows a well-ordered large scale morphology, with the polarization vectors perpendicular to the main-filament but parallel to the nearby sub-filaments. The gas kinematics traced by CO indicates a velocity gradient along sub-filaments and B-field toward the main-filament, suggesting that these filaments are possibly accretion flows to the main-filament. We use Chandrasekhar-Fermi method to estimate the B-field strength in IC5146, and the estimated field strength scales with density with a power-law index of $0.52 \pm 0.02$. The strength-density relation extends from magnetically subcritical to supercritical regime, suggesting that the magnetic flux may be removed smoothly from magnetically subcritical diffuse region. In addition to the large scale structure where our results suggests that the B-field is dynamically important, we find that the filaments in particular regions may appear randomly oriented and misalign with B-field, implying that the evolution of these filaments may be affected by strong gravity or shock.

Subject headings: ISM: clouds — ISM: magnetic fields — ISM: structure — Polarization
1. INTRODUCTION

Observations in last decades reveal that stars predominately form within clusters in magnetized and turbulent molecular clouds. Those molecular clouds often have elongated or filamentary structure of parsec scale, and are believed to directly influence the star formation process. However, how prestellar cores form in those clouds remain poorly understood. Theoretical studies suggest that both turbulence and magnetic field (B-field) inside the clouds can possibly control the star formation and cloud evolution, but their relative importance is still in debate (as reviewed in McKee & Ostriker 2007). Some numerical simulations suggest that increasing B-field strength would decrease the star formation rate to observed value (Nakamura & Li 2008; Price & Bate 2008). On the other hand, simulations assuming weak B-field suggest that the compression and fragmentation dominated by supersonic turbulence can reproduce the core mass function that is consistent with observed initial mass function (Padaon & Nordlund 2002; Mac Low & Klessen 2004). Due to the difficulty of measuring the B-field structure of molecular clouds from large to small scale, current observations are still insufficient to settle the debate.

Herschel space observatory have make great progress in revealing the detail structure in filamentary clouds. Herschel Gould Belt survey shows that the filamentary structures are ubiquitous in both quiescent and active star-forming regions, where the distribution of gravitational unstable filaments is consistent with perstellar cores (André et al. 2010; Molinari et al. 2010). The results favor the scenario that the filamentary structures are first generated in molecular clouds due to large scale magneto-hydrodynamic (MHD) turbulence and may fragment into prestellar cores after becoming gravitational unstable (Men’shchikov et al. 2010; Miville-Deschênes et al. 2010; Ward-Thompson et al. 2010). In addition, the observed filamentary structures likely share a universal characteristic width of $\sim 0.1$ pc regardless of their central column density and environment, which can be explained by
a turbulence dominated model (Arzoumanian et al. 2011). Besides, Hacar et al. (2013) discovered that particular filaments contain multiple velocity components and are likely composed of a bundles of velocity-coherent filaments based on molecular line observations. Moeckel & Burkert (2015) claims that the velocity-coherent structure can be generated in a self-gravitating hydrodynamic simulations of turbulent clouds without the need of B-field or other effects.

In contrast, optical and infrared polarizations observations toward background starlight show that the orientations of B-fields are mostly aligned and perpendicular to the long axis of main-filaments, suggesting that the B-field is dynamically important in evolution of the filaments (e.g. Franco et al. 2010; Li et al. 2013). In addition, recent observations reveal that almost all filaments have fine sub-filamentary structures extended from the main-filament, also known as striations, and the sub-filament are mostly parallel to B-field (e.g. Sugitani et al. 2011; Pillai et al. 2010). Molecular line observations show velocity gradients along striations, implying that the B-field is likely channelling the accretion gas flow toward main-filament (e.g. Palmeirim et al. 2013). These results favor strong B-field models, which assume that the cloud contraction due to turbulence or cloud-cloud collision is regulated by the B-field (Nakamura & Li 2008; Inutsuka et al. 2015). The recently released Planck all sky survey data show that most filaments are well aligned to the B-field, parallel in diffuse ISM and perpendicular in molecular clouds. The Planck results are supporting that the B-field is dynamically important in cloud evolution. However, since the resolution of Planck data is 5′, about the scale of main-filament structure for nearby molecular clouds, and the results in high density regions may be highly biased by depolarization effect, more observations toward smaller scale and denser regions are required to complete the whole picture.

It is difficult to obtain complete information of B-field with a single measurement due
to constraint of measurement methods. The commonly used methods to measure B-fields are Zeeman effect, polarization of dust emission and polarization of background stars due to dust absorption. Zeeman effect is the only tool to directly measurement the magnetic strength along line of sight. However, the effect requires strong emission from particular tracers such as CN, OH and HI in order to have significant Zeeman splitting to be detected, and therefore the number of detection of Zeeman measurements is still limited. Crutcher et al. (2010) report that the B-field strengths measured by Zeeman surveys are mostly insufficient to support clouds against gravity, while some magnetically supported clouds can still be found in the observations. Non-spherical dust grains inside magnetized clouds are known to partially align with B-fields, and therefore the light emitted or absorbed by the aligned grains will be polarized. The polarized dust emission and background starlight both trace B-field structure in the plane of sky. The former is widely used to probe the B-field structure of dense part of molecular clouds, and most of the results suggest that B-fields influence the formation of clouds and cores (e.g. Girart et al. 2006; Zhang et al. 2014). The latter probes the B-field structure within the low density part of molecular clouds in large scale efficiently, yet the spatial resolution is limited to the density of background stars.

In this work, we measure the polarization of background stars in IC5146 filamentary cloud aiming at exploring the information of B-field from main-filament scale to sub-filament scale. IC5146 is a nearby (∼460 pc) star-forming region in Cygnus, consist of a young cluster inside an HII region and a long main-filament with several extended branches. Arzoumanian et al. (2011) reveal a whole network of filaments from Herschel Gould Belt survey. The analysis based on density profile supports the argument that the filament structures form by the dissipation of large scale turbulence. However, the Planck polarization map (Planck Collaboration et al. 2015b) reveals that the filament is roughly aligned with B-field. Therefore, it is an excellent target for investigating the relative importance of turbulence and B-fields. In this paper, we perform polarization observations
of background starlight in both optical and infrared to probe the large scale B-field map in the cloud. In addition, we observe CO J=1-0 and $^{13}$CO J=2-1 in order to examine if the gas motion is confined by B-fields. The observations and data reductions are described in §2. In §3, we will present the polarization measurements in IC5146 from the combination of the multi-wavelength data and the CO map of the IC5146. §4 explains the analysis of the data. The analysis confirms that our polarization measurements are consistent with dichroic absorption scenario and tracing the magnetic structure inside the cloud, and leads to the information of magnetic strength and the correlation with gas kinematics. In §5, we discuss the detail magnetic structure in particular regions and the possible role of B-fields in formation of the filamentary cloud. The conclusion will be shown in §6.

2. OBSERVATIONS AND DATA REDUCTION

We measured the polarization of the background stars toward IC5146 filaments with several instruments; Aryabhatta Research Institute of Observational Sciences (ARIES) Imaging Polarimeter (AIMPOL; Rautela, Joshi & Pandey 2004) and Triple-Range {g’ r’ i’} Imager and POLarimeter (TRIPOL; Sato et al. 2013; Eswaraiah et al. 2015) provides optical R_c- and i’-polarimetry data, respectively, and Mimir (Clemens et al. 2007) measures the H- and K-polarization at infrared. Figure 1 shows the target fields for each instrument overlaid on the Herschel archive 250 µm image (Griffin et al. 2010; Arzoumanian et al. 2011). Almost all of the cloud is observed with Mimir, while the fields observed with AIMPOL are located mainly in the edge of the cloud in order to cover as many optical bright stars as possible. The TRIPOL fields are focusing on the northern region with longer exposure time where both bright optical and infrared stars are rare. In addition, we use Arizona Radio Observatory (ARO) 12m telescope and Caltech Submillimeter Observatory (CSO) 10.4m telescope to map the gas kinematics of CO (J=1-0) and $^{13}$CO (J=2-1),
respectively. The observed regions for ARO and CSO are also shown in Figure 1 as magenta and blue. The detailed information of the observations with different instruments are shown as follows.

2.1. AIMPOL Polarimetry

The $R_c$-band polarimetric observations were carried out toward IC5146 filamentary cloud using AIMPOL mounted at the Cassegrain focus of the 104-cm Sampurnanand telescope of the ARIES, Nainital, India. AIMPOL consists of a half-wave plate (HWP) modulator and a Wollaston prism beam-splitter coupled with a TK $1024 \times 1024$ pixel$^2$ CCD camera. The observations spanned the nights of 2011 November 4–8 and 2012 November 8–15 toward 37 fields with a diameter of $\sim 8'$. In order to obtain Stokes Q and U, we need to take images at four independent position angles ($0^\circ$, $45^\circ$, $90^\circ$, and $135^\circ$ in image coordinate system; Schaefer et al. 2007). AIMPOL is able to simultaneously measure in two position angles during single exposure. We set the integration time of 20 minutes for each two HWP angles, so each field requires 40 minutes total integration time to finish the measurements in four position angles. The polarization measurements are calibrated for instrumental polarization and zero polarization angle based on standard polarized and unpolarized stars in Schmidt et al. (1992). The data were reduced with the standard IRAF procedures $^1$, and the photometry was measured to obtain the polarization degree and angle for each star. The details of facility and procedures used to estimate the polarization degree and polarization angles (P.A.) are described in (Eswaraiah et al. 2011, 2012).

$^1$IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
2.2. TRIPOL Polarimetry

Polarimetric observations were focusing on the north-west filament inside IC5146 in g', r', and i'-bands on 2012 July 27-28 and 2014 July 6 with TRIPOL installed on the Lulin-One-meter Telescope in Lulin Observatory, Taiwan. Seven fields with size of 4′×4′ are observed in this run. TRIPOL consists of dichroic mirrors and three ST-9 512×512 pixel² CCD cameras, which enables simultaneous observations in g', r', and i'- bands. A rotatable achromatic half wave-plate and a fixed wire-grid is used to filter incoming light in given P.A.. Each field was measured at four wave-plate positions. The integration time for each position angle is 22.5 minutes, so each field requires 1.5 hour total integration time to finish the measurements in four position angles. Standard reduction procedures were applied with IRAF, and the photometry of each background star was taken with Source Extractor (Bertin & Arnouts 1996) in four HWP positions. The polarization degrees and angles for each background stars were derived from its flux in four position angles and corrected by the polarized and unpolarized standard stars from Schmidt et al. (1992). Since most stars in the observation have high extinction, and thus result in high uncertainty in g'- and r'-bands, we only use results from i'-band observations in this paper.

2.3. Mimir Polarimetry

We carried out H- and K-band polarization observations toward IC5146 on 2013 September 17–27, using Mimir instrument (Clemens et al. 2007) mounted at 1.8 m Perkins telescope located near Flagstaff, AZ and operated by Lowell Observatory. Fifty-seven fields covering IC5146 cloud are observed in H-band, and thirteen fields toward the dense regions are observed in K-bands. The field of view is 10′×10′ for Mimir, and we set 1′ overlap between adjacent fields for mosaic observations. Each field is observed in six sky dither positions where images are taken at 16 position angles of the HWP. Total 96 (16×6)
images were taken for each field with 10 sec integration for each image, and thus the total integration time is 16 minutes for each field. We took an additional short integration for those fields with saturate stars, which take 4 minutes per field. In order to calibrate the non-linearities of the camera, a series of bias images were taken with an increasing exposure time toward an illuminated flat-field screen, and the response curve of each pixel were fitted with a polynomial model to obtain a function for linearity correction. Flat fields for each HWP position were taken using a lights-on/lights-off method toward a reflection flat field screen inside the closed dome during the observation run. The data were calibrated with the Mimir Software package and the processes were described in Clemens et al. (2012a,b).

2.4. ARO CO J=1-0 mapping

In order to investigate if the B-field can confine the gas motion, we carried out molecular line observations toward 3 fields in both main filament and sub-filament with ARO 12m telescope. In November 2012, the selected fields were mapping using the on-the-fly mapping mode in the CO J=1-0 transition with the ALMA type Band 3 receiver and the filter bank spectrometer. The scan rate for our observations is set to 10″/sec, and the total integration time is ~10 hours for the three fields, resulting in a typical rms noise of ~ 0.3K at each position. The spectral resolution is 100 kHz spectral resolution, corresponding to 0.26 km s^{-1} at 115 GHz, and the spatial resolution of the observations is 20″. We used the position-switching mode for the observations and the OFF position was selected based on the Herschel map. The data were reduced with the CLASS software package\(^2\).

\(^2\)CLASS is part of the GILDAS software suite available from http://www.iram.fr/IRAMFR/GILDAS.
2.5. CSO $^{13}$CO J=2-1 mapping

The line observations toward the western part of main filament were taken using CSO telescope. In November 2014, the selected fields were mapping using the on-the-fly mapping mode in the $^{13}$CO(2-1) transition with the Heterodyne receiver and the FFTS1 spectrometer with high spectral resolution of 0.08 km s$^{-1}$ at 230 GHz. The spatial resolution of the observations is 30". The selected field is scanned with a scan rate of 12"/sec, and the total time for the observation is 25 hours. The data were reduced with the CLASS software package. Unfortunately, due to the bad weather a small region in the south-eastern corner were not covered, and the rms noise of the observations is $\sim$ 1K, much higher than our expectations. As a result, we only include the integrated map in our analysis.

3. RESULTS

Table 1-4 lists all our polarization results. Data with poor quality have already been excluded; we only select the source with polarization degree divided by its uncertainty $P/\sigma_p \geq 3$ for the $R_c$ and $i'$ polarization data, while the criteria is reduced to $P/\sigma_p \geq 2$ for H and K polarization data due to their low polarization percentage. We have further discussed the consistency of the data obtained from different instruments in Appendix A.

Figure 2(a) shows all of our polarization measurements passing the above criteria. The Herschel SPIRE 250 $\mu$m image is mainly used to represent the morphology of the cloud and compare it to our polarization data. The dust continuum map clearly shows a east-wast main filament connected to the bright cluster complex, known as Cocoon Nebula, and numerous sub-filaments are extended from the main filament. The northern region is likely the largest “sub-filament” locating on the north-west side of the main filament. Our polarization measurements show that the large scale B-field is mostly perpendicular to the
main filament, while parallel to the sub-filaments.

We compare the polarization P.A. shown in our optical and infrared data to the results from 353 GHz data of PLANCK archive in Figure 2(b)\textsuperscript{3}. We smooth and regrid the Stokes Q and U from our samples and calculate the average P.A. to match the PLANCK resolution of 5\textquotesingle. The P.A. measured in our data is similar to PLANCK results in the diffuse regions and in large scale, but become different near the dense filaments. Since PLANCK measure the polarization of dust emission over a large beam while we measure the polarization of dust absorption of background stars as point sources, it is expected that their P.A. may be different. The larger difference in denser regions implies that the B-field structure is more complicated near the filaments than in the diffuse regions, consistent with the suggestion in Planck Collaboration et al. (2014); Planck Collaboration et al. (2015a) that the polarization measured by PLANCK in the dense regions may be significantly influenced by depolarization of B-field structures.

Figure 3 shows the histogram of the extinction for all our detections, where extinction is calculated based on 2MASS data using a simple extinction law $A_V = 15.87E(H-K-0.13)$ (Lada et al. 1994, 1999). The uncertainty of $A_V$ is contributed both from the uncertainty of spectral type and observational measurements. In order to estimate the uncertainty of $A_V$, we select all the samples with negative $A_V$, and assume that the negative $A_V$ are due to the uncertainties. These samples are duplicated by multiplying -1 to their $A_V$ to reproduce a full Gaussian centred at $A_V = 0$ mag, and we derived a standard deviation of 1.02 mag from the Gaussian. Because the derived standard deviation represent the combination of uncertainty from both spectral type and observational measurements, we adopt it as our

\textsuperscript{3}Based on 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
uncertainty of $A_V$ in the later analysis. The foreground extinction can be estimated to be $\sim 0.5$ mag assuming the typical extinction per distance of 1 mag/kpc (Spitzer 1978), which is comparable to the uncertainty of $A_V$, thus the foreground stars cannot be distinguished with the 2MASS data. Nevertheless, the foreground stars are expected to be nearly unpolarized due to the low extinction and thus can be naturally excluded with our selecting criteria for polarization detections.

The ARO observations show apparent velocity gradient along the sub-filaments, while the CSO observations show global velocity gradient along the main filament. The maps and PV diagrams of these data are shown in §4.2 along with the discussion.

4. ANALYSIS

4.1. Polarization Efficiency and Grain Alignment

In order to confirm if the polarization measurements can represent the magnetic structure inside the cloud, we should examine whether dust grains are aligned with B-fields. Radiative torques (RATs) theorem (Dolginov & Mitrofanov 1976; Draine & Weingartner 1996, 1997; Lazarian & Hoang 2007) are the current well-accepted model to explain the dust alignment with B-fields, because calculations show that under typical interstellar radiation fields the alignment timescale is $\sim 10^5$ times faster than the Davis-Greenstein alignment. Since the radiation strength will decrease with the extinction, RATs theorem predicts that the efficiency for grain alignment, polarization percentage ($P_\lambda$) divided by optical depth ($\tau_\lambda$), will decrease with extinction if assuming constant dust grain size distribution. This trend has been observed by Whittet et al. (2008) with their K-band polarimetry toward Taurus, which shows a power-law decrease of $P_\lambda/\tau_K \propto A_V^{-0.52}$. They further perform a numerical simulation based on RATs theorem assuming a starless core
with external radiation field, and suggest that the simulation can explain their data up to at least $A_V \sim 10$ mag. In addition, the simulation also predict that the RATs mechanism would be inoperative as $A_V$ approach to 10 mag since the radiation that can penetrate to such high density has wavelengths too long to effectively align the grains in the model. However, the mechanism may still work in high extinction region if the dust grains have significant growth.

We plot the polarization efficiency ($P/\tau_K$, where $\tau_K = 0.084 \times A_V$) versus extinction $A_V$ for the observed sources over $3 \sigma$ detection in Figure 4. We ignore the TRIPOL i'-band data in the plot, since the sources from TRIPOL locate in a very narrow $A_V$ range, $\lesssim 4$ mag, and therefore the uncertainty of $A_V$ will highly bias the statistic. The $P/\tau_K$ versus $A_V$ is fitted with a power-law $P/\tau_K = a A_V^k$. In order to reduce the uncertainty from $A_V$ and also avoid the bias due to uneven sampling over $A_V$, our fitting is applied to the averaged data in the bins with width of $\log A_V = 0.2$. We found obvious correlations in all the groups, which are $P_{Rc}/\tau_K = (25.98 \pm 1.08) \times A_V^{-0.97 \pm 0.03}$, $P_H/\tau_K = (9.86 \pm 0.34) \times A_V^{-0.52 \pm 0.02}$ and $P_K/\tau_K = (7.90 \pm 1.54) \times A_V^{-0.58 \pm 0.09}$ for the $R_c$, $H$- and $K$-band, respectively. The power-law indices for $H$- and $K$-band $P/\tau_K$ are similar to what Chapman et al. (2011) and Whittet et al. (2008) obtained in $H$- and $K$- band ($-0.48 \pm 0.04$ and $-0.52 \pm 0.07$), respectively. However, the power-law index for $R_c$-band is significantly steeper than the $H$ and $K$ data and more consistent with the results based on the $H$ polarimetry ($-1.00 \pm 0.13$) for low $A_V$ regions ($A_V < 9.5$ mag) in Alves et al. (2014).

Two possibilities could produce the different power-law indices we obtained from $R_c$, $H$-, and $K$-band. First, if the dust grains in all $A_V$ range have the size distribution, the power-law index for the longer wavelengths should be flatter because the radiation with longer wavelengths can penetrate deeper, which appears to be consistent with our analysis. Second, since the alignment efficiency is higher for dust with size comparable to
the wavelength (Lazarian & Hoang 2007), the power-law index for H- and K-band will also become flatter in the dense regions where the dust grains are believed to grow. To distinguish which mechanism is most likely for our data and because our $R_c$-band data are mostly distributed in $A_V < 3$ mag, we separated H-band data into two groups ($A_V < 3$ mag and $A_V > 3$ mag) and fit each group with single power-law shown in Figure 5. The results show that the correlation in the two group has significantly different indices; the $A_V \leq 3$ group has a very steep index of $-0.96 \pm 0.07$, consistent with our $R_c$-band data, and the correlation in $A_V > 3$ regime tends to be flat with a index of $-0.38 \pm 0.02$. Both the power indices in the two groups are consistent with Alves et al. (2014), $-1.00 \pm 0.13$ in $A_V < 9.5$ mag and $-0.34 \pm 0.03$ in $A_V > 9.5$ mag, although the break point is at different $A_V$. The broken power-law favors the second possibility; however, the measured indices may still be influenced by the effect from first possibility, and thus decouple these two effects is required to confirm the results.

For a star with polarizations detected at multi-wavelength, its polarization degree will vary with wavelength even they are under the extinction due to the same groups of dust grains with the same $A_V$. The main reason for the variation is that penetration ability of radiation is determined by its wavelength and also the dust grains tend to be more efficient to absorb and be aligned by the radiation with the wavelength similar to the size of grains. To describe the variation in different wavelength, previous works tend to use the empirical “Serkowski relation”,

$$P(\lambda) = P_{max} \cdot exp\{-K \cdot ln^2(\lambda_{max}/\lambda)\},$$  \hspace{1cm} (1)

where $P_{max}$ is the maximum polarization at wavelength $\lambda_{max}$ (e.g. Serkowski 1973; Whittet et al. 2008; Eswaraiah et al. 2011). However, it is difficult to obtain the polarization measurements for sources at multi-wavelengths for the determination of the Serkowski relation because optical observations are often needed to acquire enough data points for fitting, and thus most of the analyses are done for the low extinction regions.
In order to study whether dust properties have changed through our polarization measurements, we perform a new method to normalize the polarization detection obtained at different wavelength to remove the variation of polarization due to the amount of radiation available for aligning the dust. Figure 6 shows that the polarization measurements at two wavelengths for the stars with multi-polarization detections. Because most our $R_c$- and $i'$-band samples locate in the $A_V < 3$ mag regions with $n \sim 3 \times 10^4 \text{cm}^{-3}$ (assuming a depth of 0.1 pc) less than the density expected for the dust coagulation ($10^5 - 10^9 \text{cm}^{-3}$ from Ossenkopf & Henning (1994)), the variations of polarization revealed in Figure 6 are likely due to the amount of the survival radiation since the data points with larger $P$ are coming from the higher extinction regions. We fit the plots with a single power-law, and adopt it as a conversion law for the polarization degree between $R_c$- and H-band and between $R_c$- and $i'$-band. The derived power-law index for conversion law is $0.79 \pm 0.04$ and $0.89 \pm 0.09$, thus $P_R$ increases more than $P_H$ and $P_i$. The nonlinear conversion laws suggest that the effect due to survival radiation could influence the power-law indices for $P$ v.s. $A_V$ by a factor of 0.79 from $R_c$- to H-band and by 0.89 from $R_c$- to $i'$ band, so our derived relations for $P_{\text{eff}}$ v.s. $A_V$ will also be affected.

The top panel in Figure 7 shows the overlap of $P/\tau_K$ v.s. $A_V$ at $R_c$-, $i'$-, H- and K-bands, and the bottom panel shows the normalized polarization efficiency for the $R_c$-, $i'$-, and H-band data sets (K-band data are ignored due to its small data sample for the derivation of the conversion law). The normalized plot reveals that most data points are overlaid with each others and behaves likely a simple power-law, whereas the H-band points with $A_V > 3$ show a flat component. The flat component is inconsistent with the Whittet et al. (2008) RATs model which predicts the polarization efficiency would have steep drop in high $A_V$ regions. Since the normalization process would remove the variation of polarization due to the amount of radiation, the normalized $P/\tau_K$ v.s. $A_V$ plot represent only the effect of dust properties. Therefore, we can confirm our previous conclusion that
the broken power-law is mainly originated from the growth of the dust grains in $A_V > 3$ mag regions. Coincidently, Chiar et al. (2011) found that $H_2O$-ice in IC5146 only exists in regions over an extinction threshold of 4.02 mag, and Whittet et al. (2001) also found a similar threshold of 3.19 mag in Taurus.

It is still a question why the break point we measured is different from 9.5 mag in Alves et al. (2014) or no break point in Whittet et al. (2008). We suspect the difference could be originated from two possible reasons. First, Whittet et al. (2008) and Alves et al. (2014) lacks of the samples in low $A_V$ regions, and thus the trends of broken power-law would be difficult to be identified. Second, the difference may come from the different levels of the star-forming activities. Since IC5146 contains several active star-forming regions instead of a starless core in Alves et al. (2014), and the internal radiation from the embedded YSOs provides additional source for aligning and heating the dust grains in the deep regions (Andersson 2012). The alignment of dust grains will increase the polarization efficiency in regions with higher $A_V$, and the heated gas possibly enhances the grain growth rate (Evans et al. 1994; Asano et al. 2013) so the dust properties may have been changed at lower $A_V$ compared to the no internal radiation case. Both of these two effects are able to move the break point toward lower $A_V$.

Our results show that even though the polarization efficiency for infrared is decreasing with $A_V$, the declination rate is smaller in high density regions possibly due to the grain growth. The dust in even $A_V \sim 20$ mag regions can still contribute polarization with a lower efficiency by a factor of $\sim 2$ comparing to $A_V \sim 5$ mag. This result is inconsistent with early studies suggesting that near-infrared polarimetry may only trace a thin surface layer of a cloud (Goodman et al. 1995). If the deep regions do not contribute polarization, the measured polarization efficiency will drop quickly as $P/\tau \propto A_V^{-1}$ since $P$ is constant.
4.2. Gas Kinematics

Our polarization measurements show that the B-field is well aligned with filament orientation. In order to examine if the B-field confines the gas dynamics, we perform CO J=1-0 and $^{13}$CO J=3-2 observations toward four sub-regions in IC5146. The four observed fields are shown in Figure 8, and fields are chosen to show the gas kinematics in different environments as stated below. Figure 9, 10, and 11 show the gas kinematics observed with CO J=1-0, and Figure 12 shows the $^{13}$CO J=3-2 integrated map.

4.2.1. CO J=1-0 Observations

Field 1 is selected to trace the filament which is parallel to B-field in the northern region. In Figure 9, the PV plot shows only one major velocity component in the filament instead of the multiple velocity-coherent structure found in Taurus B213 (Hacar et al. 2013) and the velocity component has a global velocity gradient of $\sim$0.6 km s$^{-1}$ pc$^{-1}$ along the filament, assuming a distance of 460 pc (Lada et al. 1999). The data show that the northern region has a simple kinematic structure, mainly composed of a group of gas flowing along B-field, supporting that the gas motion in the filament is coupled with B-field.

Field 2 and 3 locate in the eastern part of main filament near Cocoon Nebula, and the fields are selected across the main filament. The two fields are planned to show the variation of gas kinematics from the sub-filaments to the main filament and the velocity structure across the main filament. The large scale B-field structure in these fields is roughly in the north-south orientation. In Field 2, the orientation of sub-filament is east-west in the northern part of our field, and turns to north-south to connect to the main filament. In Figure 10, the PV plot shows a velocity gradient of $\sim$2 km s$^{-1}$ pc$^{-1}$ only in the sub-filament region and several velocity components inside the main filament without significant global
velocity gradient. The possible explanation for the velocity structure is that the gas in one nearby sub-filament parallel to the main filament is attracted by and flowing toward the main filament along B-field. On the other hand, the main filament region likely consists of at least three velocity components possibly attracting nearby gas. The gas kinematics in the main filament region seems to be independent of large scale magnetic structure, and more likely affected by the interaction between velocity components. These velocity components could be individual cores or part of the bundles of filaments; however, our field of view is too small to distinguish whether they are cores or the bundles.

In Field 3, our CO contour map shows that the region contains a elongated core-like structure in the north-west part of the field, and a north-west to south-east sub-filament. The east-west main filament is not obvious in the CO map because it is too diffuse compared to the sub-filament. In Figure 11, the averaged velocity map shows a global north-west to south-east velocity gradient likely following the sub-filament. The PV plot along the sub-filament indicates a velocity gradient of $\sim 0.6 \text{ km s}^{-1} \text{ pc}^{-1}$ along the sub-filament, and splits from one component in the sub-filament to two components in the core, likely a feature of expanding or collapsing. The core corresponds to the dense shell-like structure in the Herschel 250 $\mu$m map (see Figure 8), where our polarization measurements show an “anti-hourglass” shape, possibly stretched by expansion of the core. Expanding cores are predicted in numerical simulations (Vázquez-Semadeni et al. 2005; Anathpindika & Di Francesco 2013), which are the cores compressed by turbulence initially but re-expanding due to thermal pressure if the density is not high enough to trigger self-gravitating before the turbulence dissipate. To examine whether this region could be undergoing expanding motion, we estimate the mass per unit length of $\sim 10 \ M_{\odot} \text{ pc}^{-1}$ for the elongated core based on the Herschel SPIRE 4 bands data, which is smaller than critical mass per unit length of $\sim 20 \ M_{\odot} \text{ pc}^{-1}$ with the derived temperature of 13 K; therefore, this sub-filament is more likely to be expanding than collapsing. The gas layer pushed out by the expanding core
could be easily attracted by the main filament, and thus flowing along B-field toward the main filament and forming the sub-filament.

Our results toward the three fields are similar to the previous observation results in other molecular clouds (Sugitani et al. 2011; Palmeirim et al. 2013), suggesting the sub-filament structures are the inflow materials accreted along magnetic field lines onto the main filaments. In addition, the existing of expanding core supports that the cloud was once be compressed by turbulence or shock which has been dissipated now, supporting that the MHD turbulence may be dynamically important in early stage of the filament evolution (Arzoumanian et al. 2011, 2013).

4.2.2. $^{13}\text{CO} \ J=3-2$ Observations

We also perform the $^{13}\text{CO} \ (J=3-2)$ observation toward the western part of main filament (Field 4 in Figure 8). Since the data is too noisy to analysis the line width or detail structures, Figure 12 only shows the integrated maps for two velocity ranges in the blue component ($V_{\text{LSR}} = 2-3.5\text{km/s}$) and the red component ($V_{\text{LSR}} = 3.5-5\text{km/s}$). The map shows that the red component is mainly located in the two ends of the main filament, matching the dense cores in dust continuum map, and the blue component mostly comes from the central part of the main filament. The velocity difference between dense cores and filaments reveals a global velocity gradient along the filament, implying the gas in the main filament may be accreted towards the cores. This result suggest that this field likely contains two hub-filament structures at two ends, where nearby converging filaments are accreted toward the center dense hub (Myers 2009). In addition, the velocity gradient is perpendicular to the B-field unlike the sub-filaments in Field 1–3, suggesting that the B-field in the western main filament seems not strong enough to confined the gas. Since the velocity gradient is toward the dense hubs, the gravity is more likely the dominated
mechanism in this region.

4.2.3. Estimations of Velocity Dispersion

In order to estimate the strength of the turbulence, we calculate the line-of-sight velocity dispersion based on our CO J=1-0 data. We first derived the intensity weighted dispersion maps for Field 1–3, and the pixels with less than 3σ detections or likely multiple velocity components are excluded. Then the observed line-of-sight velocity dispersion $\sigma_{\text{obs}}$ of the three fields are derived from the average intensity weighted dispersion of the three maps with the contribution from channel width (0.26 km s$^{-1}$) removed, and the values are $0.55 \pm 0.39$, $0.52 \pm 0.23$, and $0.57 \pm 0.24$ km s$^{-1}$ for Field 1–3, respectively, where the uncertainty is the dispersion of $\sigma_{\text{obs}}$ over the map. The $\sigma_{\text{obs}}$ in the three maps are similar, and thus we adopt the averaged $\sigma_{\text{obs}}$ over the three fields of 0.55 km s$^{-1}$ for the later calculations.

Assuming the velocity dispersions contributed by all molecular species are independent and could be added in quadrature (Myers 1983), the non-thermal velocity dispersion can be derived by:

$$\sigma_{nT} = \sqrt{\sigma_{\text{obs}}^2 - \sigma_T(\mu_{\text{CO}})^2}$$ (2)

where $\sigma_T(\mu) = \sqrt{k_bT/\mu_{\text{CO}} m_h} = 0.05$ km s$^{-1}$ is the thermal velocity dispersion contributed by CO, and the temperature we adopted is 10 K based on Herschel data. The total velocity dispersion is derived by:

$$\sigma_{\text{tot}} = \sqrt{\sigma_{nT}^2 + \sigma_T(\mu)^2} = 0.58 \text{ km/s}$$ (3)

where $\sigma_T(\mu) = 0.19$ km s$^{-1}$ is the dispersion contributed by all species using a mean molecular weight of 2.33.

The velocity dispersions in IC5146 were also estimated by Arzoumanian et al. (2013)
using $N_2H^+$ and $C^{18}O$ toward several points over the cloud with IRAM 30m data and Graham (2008) using $^{13}CO$ toward western part of main filament based on JCMT HARP Gould Belt Survey data (Ward-Thompson et al. 2007). Velocity dispersion derived is $\sim$0.23–0.32 km s$^{-1}$ and $\sim$0.35–0.55 km s$^{-1}$ for the former and latter, respectively. Our results are more similar to Graham (2008) but about two times as large as in Arzoumanian et al. (2013). The difference may be due to the traced depth with different tracers. $CO$ is tracing more diffuse regions than $^{13}CO$ and $C^{18}O$, and thus the velocity dispersion derived from $CO$ would be overestimated due to the velocity structures along the line of sight. In previous sections, we have shown the global velocity gradient in our data, and thus the velocity dispersion along line of sight is expected to be non-negligible. On the other hand, $C^{18}O$ and $N_2H^+$ are tracing the gas kinematics mostly in high density regions which may be different from the diffuse regions. Combing the results from different tracers, the velocity dispersion over the whole cloud can be estimated as 0.23–0.55 km s$^{-1}$. The velocity dispersion range is corresponding to Mach number of 1.5–2.7, suggesting that the supersonic turbulence is not currently strong in the cloud.

4.3. Estimation of Magnetic Strength

Chandrasekhar & Fermi (1953) shows that the strength of B-field in the plane of sky ($B_{P.O.S}$) can be estimated by the dispersion of measured polarization orientation ($\delta \phi$), the line-of-sight velocity dispersion of the gas ($\delta v_{L.O.S}$) and the volume density of the gas ($\rho$). Ostriker et al. (2001) further put a modification factor of 0.5 in front of the Chandrasekhar-Fermi method to account for the complicity of the magnetic field and the density structure,

$$B_{P.O.S} = 0.5 \cdot (4\pi \rho)^{0.5} \cdot \frac{\delta v_{L.O.S}}{\delta \phi}; \delta \phi \leq 25^\circ. \quad (4)$$

Since we have large number of polarization detections ($\sim 2000$) over this cloud, we are able
to use Eq. 4 to show the large-scale magnetic field distribution and to study the distribution of magnetic enhancement along with the cloud density (§5.2).

Because the density of the regions traced by $^{18}C$O ($\sim 10^{21} - 10^{22} cm^{-2}$) is close to the $A_V$ range of our data ($\sim 1$–20 mag), we adopt the velocity dispersion derived from $^{18}C$O, $\sim 0.3$ km s$^{-1}$, by Arzoumanian et al. (2013) for the field strength calculation. The constant velocity assumption is adequate for the whole cloud, since 96% of our polarization measurements is in $A_V < 10$ mag range (Fig. 3) and Arzoumanian et al. (2013) shows that the velocity dispersion in diffuse filaments is nearly constant until $N_{H_2}$ reaches $\sim 2 \times 10^{22}$ cm$^{-2}$ or $A_V \sim 10$ mag. For $A_V > 10$ mag, the velocity dispersion will slightly increase with $N_{H_2}^{0.35}$, which will cause the field strength underestimated by a factor of $\sim 1.3$ for $A_V = 20$ mag.

In order to estimate the volume density used in Eq. 4, we calculate the column density by fitting grey-body function to Herschel data at 160, 250, 350, and 500 $\mu$m with the dust opacity $\kappa_\nu = 0.1 \times (\nu/1000$GHz)$^2$ cm$^2$/g (Könyves et al. 2010). We assume that the filaments are cylindrical and thus their thickness are the same as their width. Arzoumanian et al. (2011) measure the width of the filaments in IC5146, and suggests they share a common width of 0.1 pc, which we adopt as the thickness of the cloud to produce a volume density map. We note that the distance used in Arzoumanian et al. (2011) is $460^{+40}_{-60}$ pc derived from star counts by Lada et al. (1999). However, some studies obtain a distance of $950 \pm 80$ pc based on the main sequence defined by the spectroscopy and photometry of the B-type stars in the Cocoon Nebula (e.g. Harvey et al. 2008). If the true distance of IC5146 is indeed 950 pc, the filament width would be underestimated by a factor of 2 and the volume density we obtained is overestimated by a factor of 2.

To obtain the dispersion of measured polarization orientation, each polarization detection is selected along with nearby detections within a 7$'$ box as a group. The $\delta\phi$ of
each group is calculated from the dispersion of the P.A.s and the dispersion due to the observational uncertainty is removed. If a star has detections at multi-wavelengths, each detection is considered as different vectors because the polarization at different wavelengths may trace the B-field in different depth; however, only $\sim 10\%$ of our samples have detections at more than one wavelengths, thus it only have minor effect. The magnetic strength of each group is derived with Eq. 4 using the mean volume density over the beam and a constant velocity dispersion of 0.3 km s$^{-1}$. We exclude those groups with too large dispersion of P.A.s which cannot meet the either of the following three requirements: (1) $\delta \phi \leq 25^\circ$ in Ostriker et al. (2001), (2) the intensity of at least three of the four Herschel bands is over 3 $\sigma$ to provide a meaningful column density measurements, (3) or the derived magnetic strength cannot reach 3$\sigma$ level. The magnetic strength map and its uncertainty is shown in Figure 13.

In order to quantify the relative importance of gravity and B-field in the cloud, we also calculate the mass-to-magnetic flux ratio $\lambda$ using

$$\lambda = \left( \frac{m_{H_2} \times N_{H_2}}{B} \right) \left( \frac{1}{2\pi G} \right)^{1/2}$$

(5)

where $m_{H_2} \times N_{H_2}$ is the mass column density and $B$ is the magnetic strength (Nakano & Nakamura 1978). $\lambda$ indicates whether the B-field is strong enough to support the gravity. For $\lambda > 1$, the cloud is supercritical, meaning it is self-gravitating, but for $\lambda < 1$ the cloud is magnetically supported. The $\lambda$ map is shown in Figure 13(c). The map reveals that the diffuse regions in the cloud tend to be subcritical; however, the dense filaments are mostly transcritical or supercritical. We also labels the YSO candidates identified in Harvey et al. (2008) on the map, and the YSO candidates mostly locates in $\lambda > 1$ regions, suggesting that the $\lambda$ is one of the threshold for star formation. We further plot the B strength v.s. $n_{H_2}$ with the critical $\lambda$ indicated in Figure 14. The plot reveals that the $\lambda$ is smoothly varying from subcritical to supercritical as the increase of density, suggesting B-field is
dynamically important in the diffuse regions while the magnetic flux is gradually removed and become less important in the dense regions. Figure 14 also shows how the estimation of B-field strength and volume density shift with a vector if the correct distance of IC5146 is 950 pc instead of 460 pc. Note that the power index (the slope of the line in the log-log plot) will not change for any scaling factors. The influence of the uncertain distance is that the fraction of supercritical samples will increase; however, the overall distribution of B strength v.s. \(n_{H_2}\) is not changed. Thus, our main conclusion is still valid even if the distance is doubled.

To investigate the relative importance of turbulence and B-field, it is useful to estimate if the turbulence in the cloud is super- or sub-Alfvénic. We note that even though the simulations in Falceta-Gonçalves et al. (2008) suggests that the equipartition assumption used in Chandrasekhar-Fermi method is valid in both super- and sub-Alfvénic conditions, the criteria \(\delta \phi \leq 25^\circ\) in Eq. 4 is equivalent to Alfvén Mach number \((M_A) < 0.87 \cdot \cos(\theta)\) where \(\theta\) is the inclination of B-field \((M_A\) depends only on \(\delta \phi\)). Thus, the samples pass our three requirements for field strengths calculations are certainly sub-Alfvénic. For all the positions with \(\delta \phi\) measurements and 3\(\sigma\) magnetic strength detection, 34\% of data do not pass the \(\delta \phi \leq 25^\circ\) requirement, but they are not necessarily super-Alfvénic because the larger \(\delta \phi\) may be resulted from the complicated magnetic field morphology.

For the regions pass all the three requirements, the median Alfvén velocity is derived as \((0.78 \pm 0.83)/\cos(\theta)\) km s\(^{-1}\) based on the B-field strength and density shown in Figure 14, and the corresponding median \(M_A\) of \((0.38 \pm 0.21) \cdot \cos(\theta)\). Our results show that the sub-Alfvénic regions are distributed around the whole filament structure, consistent with Li et al. (2014) and Planck Collaboration et al. (2015b) that the alignment of the filament and B-field is a signature of sub-Alfvénic turbulence. The role of B-field over the cloud will be discussed in §5.2.
5. DISCUSSION

5.1. Evolution Status in Particular Region

Figure 2 shows that the large scale magnetic morphology in IC5146 is mostly well aligned with the filamentary structure, perpendicular to the east-west main filament and parallel to the northern north-south filament. The bimodal alignment of B-fields with filamentary clouds have been shown in many observations in (e.g. Sugitani et al. 2011; Palmeirim et al. 2013; Li et al. 2013). The well-ordered and -aligned B-field favors the models in which the B-field is strong enough to channel diffuse medium and guide the contraction due to gravity, shock or large scale turbulence to form a sheet-like structure (e.g. Li et al. 2008; Nakamura & Li 2008; Inutsuka et al. 2015).

Since recent Herschel data reveal that the large scale filamentary cloud in fact consists of numerous filamentary sub-structures, and the global orientation of the whole cloud is possibly not consistent with local orientation (e.g. Andrés et al. 2010; Arzoumanian et al. 2011; Palmeirim et al. 2013). It is thus interesting to examine how the local filamentary structure interact with B-field and if it is consistent with the result from comparison between B-field and large scale morphology of the cloud. Here we divide IC5146 into four sub-regions shown in Figure 1 and discuss their evolutionary status in the following subsections.

5.1.1. The Cocoon Nebula

Cocoon nebula is a bright HII region heated by a B0 V star BD +46°3474 inside a star forming cluster. Figure 15(a) shows our polarization measurements on the Herschel 250 µm image. The filamentary structure located close to the edge HII region is likely a shell structure around BD +46°3474. Our polarization detections are located around the HII
region and inside the center dust cavity, but only few detections are inside the dense ridge of the shell. Surprisingly, the B-field in the whole region is still ordered, and the polarization orientations over the region distribute likely a single Gaussian shown in Figure 15(b) with an average of $12^\circ.7 \pm 31^\circ.6$. The uniform large scale B-field near HII region is unlike other HII regions where the B-field is compressed by the expanding front (e.g. Santos et al. 2014).

The shell-like structure implies that the region was likely compressed by the shocks from the center star, which is one of the potential origin of the filament 16–19 identified by Arzoumanian et al. (2011). Numerical simulations show that the converging flows compressed by super-Alfvénic turbulence or shock (e.g. Hartmann et al. 2001; Padaon et al. 2001) can result in filaments with orientation perpendicular to local shock front and random in large scale. In addition, the simulations suggest that the B-field inside the filaments are parallel to the orientation of filaments. These models are supported by the analysis in Arzoumanian et al. (2011) based on the radial density profiles of filaments, suggesting a universal characteristic width of $\sim 0.1$ pc with the assumption of the Larson’s Law.

For the observed filaments and B-field morphology, the orientations of filaments in the HII region are random and do not show significant alignment with large scale B-field, consistent with the super-Alfvénic models instead of strong B-field models. However, the super-Alfvénic models predict a random oriented B-field in large scale while it is uniform shown in our results. The inconsistency can be explained if the compression of super-Alfvénic shock is only efficient in small scale near the dense ridge, and thus the B-field inside the ridge may turn to parallel to the filaments. Since most of our polarization detections are outside the dense ridge, our results can only reveal the large scale B-field structure. Following the explanation, we suspect that the Cocoon Nebula may evolve via two stages: i) The large scale structure of the molecular cloud possibly first formed from the contraction regulating by strong B-field and forming a main filament (as in Nakamura
The stage can explain the ordered large scale B-field and the structure of whole IC5146, and also provide a high density conditions suitable for the formation of cluster and HII region. ii) The B star and the star forming cluster may form from the main filament, and the induced super-Alfvénic shock could compress the nearby material. The shock compression is probably limited in local regions and thus results in a second-generation filaments without affecting the large scale B-field. The stage can explain the origin of sub-filamentary structure in Cocoon Nebula with the orientations inconsistent with the large scale orientation of both B-field and main filament.

5.1.2. The Eastern Part of Main Filament

This region denotes the cloud between the hot HII region and the active star-forming region in the western side. The column density derived based on Herschel data indicates a mass-per-unit-length of $4 \, M_\odot \, pc^{-1}$ (Arzoumanian et al. 2011), suggesting that the cloud is thermally subcritical and thus non-self-gravitating. Figure 16(a) and (b) show the polarization map and the histogram of P.A in this region. Even though the polarization maps show that the B-field is well aligned with the main filament, the histogram reveals the existence of two components, one major component perpendicular to the filament $(22^\circ 1 \pm 21^\circ 7)$ and one minor component parallel to the filament $(-61^\circ 3 \pm 16^\circ 4)$. In Figure 16(c), we plot the P.A.s v.s. the projected distance along the main filament, represented by the green line. The distribution in Figure 16(c) is consistent with what we see in histogram that bimodal distribution of P.A exist in this region either parallel or perpendicular to the filaments. In addition, Figure 16(c) also shows that the bimodal distribution is evenly distributed along the filament, implying that they are not only local phenomenon.

The bimodal distribution of P.A. was observed in other clouds in early studies (e.g. Goodman et al. 1990), and it is explained by a multi-layers model with different B-field
orientations in different layers. The observed polarization is an integrated quantity along the line of sight, thus the values at different positions depend on the relative thickness of layers the light of the observed stars penetrated. Therefore, the polarization map from all the measurements can reveal multiple components tracing different layers.

The multi-layers can be separated clouds or internal structures inside a cloud. In order to examine which structure can better explain the bimodal P.A. in the region, we select the data from the two components to investigate whether their extinction, polarization degree, polarization efficiency and color-color distribution are different (Figure 17). The histograms reveal that those data from the two components share similar range in extinction and polarization. The color-color diagram shows that the background stars are all consistent with the main-sequence stars, suggesting that the measured P.A. are not contaminated by circumstellar disks of YSOs or envelopes of AGB stars.

If the multi-layers are separated clouds along the line of sight, the bimodal P.A. can be resulted from the two conditions: i) Some stars are located between layers showing the field only in the front layer, while the background stars give the integrated field direction. In this case, the latter will therefore go through higher column density and higher maximum extinction than the former. Since the minor component have the similar extinction range with the all sample, this condition is not valid for our sample. ii) The relative thickness of layers change with positions, and the detected field direction at each position will reflect only the direction in the thicker layer due to the depolarization effect. However, the distributions of polarization degree and the polarization efficiency vs. $A_V$ of the two components are both similar to the trend in Figure 5, implying no significant depolarization effect occurring in this region. Based on the above analysis, the more convincing possibility is that the multi-layers are the internal structure of the cloud. In the case, the B-field of the cloud in particular regions turn to parallel to filament, and the observed P.A. vary as well.
Numerical simulations suggest that the filaments generated by strong turbulence will have internal B-field parallel to filament (Padoan et al. 2001); however, even though the observed minor component have higher fraction in higher $A_V$, more samples of major component also locate in the same high $A_V$ regions and still have B-field perpendicular to filament. To explain the inconsistency, we suspect that the measured minor component may only come from local regions in small scale. Our polarization detections are measured using background stars, which trace the integrated polarization in a pencil-beam size region, and thus are able to detect the local polarization structure in small scale. Tafalla et al. (2015) suggests that the turbulence and self gravity may cause the large scale filament to fragment into bundles of fibers in small scale parallel to large scale filament, which might be the origin of the minor components. Our CO map shown in Figure 10 and 11 also reveal several velocity components in this region, which is consistent with our suspicion. However, our spatial sampling rate is insufficient to map the detailed structure of minor component, we can only use statistical approach to roughly estimate their properties.

Here we adopt two statistical approaches to estimate the spatial properties of the minor component. The first approach is using the local sampling rate to estimate the size scale. For each measured background stars in the minor component, their angular separation to their nearest samples are derived as the minimum sampling spacing. The average of the minimum sampling spacings for all samples in minor component, $0.96 \pm 0.60'$ or $0.13 \pm 0.08$ pc. Since our sampling rate is not sufficient to resolve the small scale structure, $0.09 \pm 0.083$ pc then is the upper-limit for the size of the structure.

The second approach is following the concept of Monte-Carlo method to estimate the fraction of area occupying by the minor component. The basic idea is that if all the detections of background stars are treated as test particles, the portion of detections in the minor component to the total detections will be expected to be the portion of area of the
minor component to the total area. However, because our sampling is not uniform over the cloud due to extinction, a correction factor should be applied to achieve fair statistics. We assume the background star field is uniform over the cloud and thus adopt the number distribution over extinction \((N(A_V) \text{ in Figure 3})\) to calibrate the observed sampling rate. The number fraction between the minor component and all samples can be calculated with each detection weighted by \(W(A_V) = \frac{1}{N(A_V)}\), which reproduces a uniform sampling rate over \(A_V\):

\[
\text{Fraction}_{\text{minor/all}} = \frac{\sum_{i=0}^{N_{\text{minor}}} W(A_V)}{\sum_{i=0}^{N_{\text{all}}} W(A_V)} = 0.12.
\]

The fraction represents that only \(\sim 12\%\) of the area belongs to the minor component, which provides a observable quantity for examination of models.

### 5.1.3. The Western Part of Main Filament

This region contains the thermally super-critical part of the main filament, and also an active star forming region where numerous young stellar objects are identified by Spitzer and Herschel (Harvey et al. 2008; Arzoumanian et al. 2011). It consists of at least two parallel filaments and two hub-filament structures (HFS) at two ends. Figure 18(a) and (b) shows the polarization map and the histogram of P.A in the region. The histogram of P.A. mainly show one peak with an average of \(14^\circ \pm 29^\circ\), but the distribution is asymmetric with a tail to the negative instead of a simple Gaussian.

Figure 18(c) also shows the variation of B-field versus the projection distance along the main filament from all the samples in the white box and the samples near the dense filament in the black box. For the all samples, the field is mostly perpendicular to main filament, P.A. \(\sim 14^\circ\) in the middle part, but smoothly increase to \(\sim 40^\circ\) to left end. One component with P.A. \(\sim -30^\circ\) appears when the projection distance is larger than \(1400''\) and the P.A. become diverse. The samples near the dense filament show similar trends as
all samples, but the diversity is relatively lower in the western part. These results suggest that the variation of B-field direction exist both inside and outside of the main filament, but the diversity of P.A. is much larger outside of the main filament. The large diversity is likely due to the HFSs; we can see in the polarization map there is large scale curvature around the two HFSs. We note that the bimodal P.A. distribution discovered in eastern part of main filament can be barely seen, but it is mixed with the large scale curvature near HFSs and therefore indistinguishable in the histogram.

Our $^{13}$CO data (Figure 12) shows that the gas inside the main filament is likely flowing toward the dense hubs at the two ends, which may be the origin of the large scale curvature of B-field. The mass-to-magnetic flux estimation shows that the region is magnetically transcritical (Figure 13(c)), where the gravity is possibly strong enough to overcome the magnetic energy. Thus, the gas in the region collapses roughly in the direction perpendicular to B-field and drags B-field to the gravitational potential well, likely the two HFSs at the ends. In our data, the large scale curvature is not obvious in the middle but become significant as approaching to the two ends, which is consistent with the gas flow and the location of gravity potential well. Therefore, our results suggest that the region is evolving from initially strong B-field condition (with a uniform large scale B-field perpendicular to the main filament) to a strong gravity condition (dragging the gas and as well the large scale B-field toward the two HFSs). In numerical simulations, Gómez & Vázquez-Semadeni (2014) shows that a self-gravitating cloud will naturally evolve to a dynamical HFS where the radiate sub-filaments are the collapsing flows accreting toward the dense hub. Although this simulation does not include B-field, it describes the possible evolution under strong gravity condition.

In addition to the HFS, the other important feature in this region is the filaments with similar orientation parallel to the large scale filament. Nagai et al. (1998) and Busquet
et al. (2013) suggest that the parallel filaments may be evolved from sheet-like structure which fragments along B-field due to the instability of self-gravity. These models can explain our observations, since the parallel filaments are perpendicular to the B-field and their mass per unit length are thermally supercritical (Arzoumanian et al. 2011).

5.1.4. The Northern Region

The northern region denotes the region to the north of main filament. It contains mainly two thermally subcritical filaments; we name them N1 and N2. Figure 19(a) and (b) shows the polarization map and the histogram of P.A.. In the histogram, the samples near Filament N1, N2 and the whole northern region are plotted. The detections around the whole region have an average of $4^\circ \pm 29^\circ$ which is likely composed by two components peaked at $5^\circ$ and $25^\circ$. The detections near the filament N1 have an average of $15^\circ \pm 24^\circ$ with both $5^\circ$ and $25^\circ$ components. On the other hand, the detections near filament N2 have more diverse P.A. but lack of the component peaked at $25^\circ$.

We also plot the P.A. vs. projection distance along Filament N2 in Figure 19(c) for the samples near Filament N1 and N2. The plot reveals two components; one is parallel to Filament N1 ($\sim 10^\circ$), and the other is perpendicular to Filament N2 ($\sim -30^\circ$). The former is more widely distributed over the whole region; however, the latter is only shown near Filament N2. The variation of P.A. between the two components may originate from curvature of B-field or the integration effect from two layers of clouds with different orientation of B-field. The most common mechanism to curve the B-field is via gravitational collapsing perpendicular to B-field or compression due to shocks or turbulence. However, Filament N2 is thermally subcritical and thus significant gravitational collapsing is not expected. Furthermore, theoretical simulations show that the the compression due to shocks or turbulence tend to morph the B-field to parallel to filaments (Padaon et al.
inconsistent with our observations. Therefore, it is more possible that Filament N2 is another separated layer with B-field perpendicular to the filament while Filament N1 is possibly connected to the main filament with an average B-field of $\sim 14^\circ$.

A velocity gradient of $0.7 \, \text{km s}^{-1} \text{pc}^{-1}$ along the filament direction is detected in the filament N1 by our CO data shown in Figure 9, indicating the filament is possibly flowing and accelerating along the B-field toward the main filament. The filaments parallel to B-field are likely accretion flows to replenish the main filament (Nakamura & Li 2008; Palmeirim et al. 2013) (See discussions in §5.3.1).

5.2. The Magnetic Strength Scaling with Density

How the B-field scale with volume density can hint how the clouds collapse. In a weak B-field case, the cloud would contract nearly isotropic, and thus the B-field would scale with density by $B \propto n^{2/3}$ (Crutcher 2012). On the other hand, if the B-field is dynamically important, the gas would tend to contract along B-field and the scaling power index would be less than $\frac{2}{3}$ (Tritsis et al. 2015); for example, an index of $\sim 0.47$ is predicted by the ambipolar diffusion model (Fiedler & Mouschovias 1993). Crutcher et al. (1999, 2010) summarize the measurements of B-field strength from Zeeman survey; however, the scaling index of $0.47 \pm 0.08$ derived in Crutcher et al. (1999) is inconsistent with the result in Crutcher et al. (2010), $\sim 0.65$. Even though Crutcher et al. (2010) suggested that the inconsistency is due to the smaller sample set in the earlier study, it may imply that the scaling index measured in different sample sets are probably biased by the diversity of molecular clouds; the index derived from any single cloud could be much different from the average value. As an example, Li et al. (2015) show a scaling index of $0.41 \pm 0.02$ from several measurements toward NGC6334 in different scales. On the other hand, Tritsis et al. (2015) argue that three assumptions Crutcher et al. (2010) used could be problematic; they
are a constant B-field strength in the low density regime, low uncertainty of density, and a flat distribution of intrinsic B-field strength. With their proposed corrections, they derive an index of $\sim 0.5$, although they also found that KS-test accept both 0.65 and 0.5 values.

Based on our data, we show a complete measurements of $B_{pos}$ v.s. $n_{H_2}$ for $n_{H_2} \sim 10^3 - 6 \times 10^4$ cm$^{-3}$ in Figure 14. Our data all locate in the regime of $n_{H_2} > 150$ cm$^{-3}$ in Crutcher (2012) plot where the magnetic strength is expected to increase with density. Figure 14 shows a power-law scaling with an index of $0.52 \pm 0.02$ similar to 0.47 in Crutcher et al. (1999) and $\sim 0.5$ in Tritsis et al. (2015) which is consistent with the ambipolar diffusion model.

One of the intriguing features is that the magnetic strength of the most samples are tend to be bounded in the subcritical regime for $n_{H_2} > 3000$ cm$^{-3}$ instead of increasing along the trends as in the low density regime. Thus, the number of samples is much lower in supercritical than subcritical regime in the similar density range. The feature is possibly due to the mechanism to remove the magnetic flux which may only be efficient in particular conditions or require a relatively long evolutionary timescale.

In order to investigate the possible origin to increase the mass-to-magnetic flux ratio, Heitsch & Hartmann (2014) estimated the diffusion time-scales for sheets and filaments with “accretion along B-field”, “ambipolar diffusion”, “turbulent ambipolar diffusion”, and “fragmentation” to investigate their relative importance. Since the physical conditions in IC5146 are diverse, we choose two parameter sets to roughly represent the physical conditions. The first set is for the diffuse regions with density of $\sim 3000$ cm$^{-3}$, B-field strength of $6 \mu$G, and length scale of $\sim 1$ pc. The second set is for the dense regions with density of $\sim 30000$ cm$^{-3}$, B-field strength of $40 \mu$G, and length scale of $\sim 1$ pc. For the sheet model, the turbulence ambipolar diffusion is more efficient in the diffuse regions, and the accretion is dominating in the dense regions; however, both parameter sets locate near
the boundary between turbulent ambipolar diffusion dominating and accretion dominating regimes, and thus the dominating mechanism highly depends on the accurate conditions. For the filament model, the dominating mechanism is also possibly the turbulent ambipolar diffusion or accretion depending on the accurate length scale in the diffuse regions, and the accretion is more likely dominating in the dense regions. Our observations show that the gas near main filament is likely flowing toward the main filament, which seems supporting the accretion mechanism. On the other hand, the scaling index of 0.52 is consistent with the prediction of ambipolar diffusion. Thus, the two mechanisms are both possibly working in IC5146.

5.3. The Formation and Evolution of Filaments

5.3.1. The bimodal Alignment to B-field

Most filaments in IC5146 are found to be parallel or perpendicular to B-field. The similar bimodal alignment is also found from large sample statistics (Li et al. 2013; Planck Collaboration et al. 2014). However, the origin of the bimodal alignment is still unclear. Planck Collaboration et al. (2014) suggest that the bimodal alignment is possibly related to their column density; the parallel cases are usually found in diffuse ISM while the perpendicular cases appear in the molecular clouds. In order to examine whether the bimodal alignment is determined by the column density, we select some filaments for both cases in IC5146 and adopt the mass per unit length ($\mu$) estimated by Arzoumanian et al. (2011).

The filament N1 (filament 14, the id used in Arzoumanian et al. (2011)) and some sub-filaments parallel to B-field (filament 3, 21 and 23) have $\mu$ of 13, 2, 6, and 7 $M_\odot$/pc, respectively. On the other hand, the filament N2 (filament 4) and the main filament
(filament 6, 13, 15, and 24) perpendicular to B-field have \( \mu \) of 8, 152, 23, 4, and 21 M\(_\odot\)/pc. Comparison of these two groups show that even though the parallel group has statistically lower \( \mu \) than perpendicular group, the filament N1 with higher \( \mu \) of 13 M\(_\odot\)/pc can still be parallel and the eastern part of main filament with low \( \mu \) of 4 M\(_\odot\)/pc can still be perpendicular. These particular cases suggest that the density may not be the only factor to determine the filament alignment.

One possible scenario to explain our results is that the filaments parallel to B-field are still a dynamic flow due to gravity and confined by B-field while the filaments perpendicular to B-field are stationary along the B-field direction. The dynamical flow will eventually reach the stationary state and become perpendicular to B-field. Since the free-fall time scale is determined by the density, the clouds with higher density tend to be perpendicular to B-field because it has shorter dynamical timescale to reach stationary. Therefore, some dense filaments can still be parallel to B-field due to their young dynamical age, and some diffuse filaments can still be perpendicular to B-field if they are old enough. Our estimation of B-field strength shows that all the filaments parallel to B-field are magnetically subcritical, supporting that they are confined by B-field. In addition, our CO data shows that the filament N1 has a large scale velocity gradient along the filament (Figure 9) and the eastern part of main filament only show velocity gradient in the sub-filament near the edge of main-filament which is parallel to B-field (Figure 10–11). Similar results are also obtained in previous observations and simulations that the filaments parallel to B-field are likely the accretion flows toward the main filament (e.g. Nakamura & Li 2008; Palmeirim et al. 2013; Li et al. 2015).
5.3.2. Filament Category and the Filament Formation in IC5146

In the previous sections, we show that the filaments in IC5146 may be formed via different conditions and mechanisms. In order to investigate the possible formation mechanism, we propose to establish a system to categorize the filaments for future detailed studies. Here we summarize the feature and possible formation mechanism for four types of filaments seen in IC5146.

I) The main filament: The most obvious filamentary structure with a length of few to tens pc. It may consist of several velocity-coherent filaments parallel to the main-structure (Hacar et al. 2013). The orientation of the main filament is perpendicular to a well ordered large scale B-field (e.g. Chapman et al. 2011), and nearby material could be accumulated toward the main filament along B-field (e.g. Palmeirim et al. 2013). Based on the alignment to B-field, this type of filaments is likely generated via the contraction channelled by B-field (Nakamura & Li 2008; Inutsuka et al. 2015). These filaments can be either thermally or magnetically subcritical or supercritical.

Ia. (Thermally) Subcritical main filament: Observations suggest that the thermally subcritical filaments are formed before star formation (Andr´e et al. 2010). This type of filaments does not show significant large scale velocity gradient possibly because the B-field and thermal pressure can support the filament and prevent large scale collapsing.

Ib. (Thermally) Supercritical main filaments: The thermally supercritical main filament possibly with active star formation (Andr´e et al. 2010). The gas inside the filaments might shows a large scale velocity gradient along the filament toward the dense part, and the B-field shows large scale curvature possibly due to the contraction along the
filaments (e.g. Kirk et al. 2013; Sugitani et al. 2011). The features suggest that the gravity is comparable or even stronger than B-field to induce the filament contract perpendicular to B-field. This type of filaments may consists of several filaments parallel to each others, which could be due to the gravitational fragmentation along B-field (Nagai et al. 1998; Inoue & Inutsuka 2008, 2009; Busquet et al. 2013).

II) Accretion filaments: Similar to the “stripations” discovered in previous studies (e.g. Sugitani et al. 2011; Palmeirim et al. 2013; Matthews et al. 2014), these filaments are thermally subcritical and has a large scale velocity gradient along the filaments. The B-field near the filaments are mostly uniform and parallel to the filaments, and likely confine their gas dynamics. This types of filaments tend to be diffuse (Planck Collaboration et al. 2014).

III) Hub-filament structures (HFS): A dense hub connected with several converging filaments, and the hub often hosts cluster forming regions (Myers 2009). The orientations of filaments connected to the hub are nearly random and might not be well aligned to large scale B-field. In addition, the velocity gradients toward the center hub are in the directions along the converging filaments, suggesting that the gas kinematics are likely dominated by gravity (e.g. Liu et al. 2012; Kirk et al. 2013).

IV) Compressed filaments: Filaments can also be produced via the compression of shocks or turbulence. Simulations show that the B-field inside these filaments are parallel to them but not consistent with large scale B-field, suggesting that the influence of B-field is not dynamically important (Padaon et al. 2001). The most convincing compressed filaments are those correlated to the shock from OB stars (e.g. Peretto et al. 2012; Cashman & Clemens 2014). This type of filaments often have arc shape consistent with
the compression front from the shock sources or are random oriented if the compression is caused by small-scale turbulence.

Even though the four types of filaments are formed in different conditions, their evolution may still relate with each others. Here we propose a possible scenario which can explain the relation of the types of filament in IC5146 which is outlined in Figure 20(a)–(f). The processes in each step are: (a) A massive main filament perpendicular to B-field forms under large scale contraction in strong B-field and sub-Alfvénic environment. (b) After the main filament formed, the nearby accretion filament may be still flowing toward main filament and replenishing the main filament and remove the magnetic flux as well. (c) The main filament gradually become thermally supercritical. (d) The thermally supercritical main filament possibly fragment along B-field and become parallel filaments due to gravitational instability and confinement of magnetic pressure. (e) As the main filament reaches magnetically supercritical, the gravity can force the gas to flow along main filament perpendicular to B-field toward density peak or possibly result in collision of the parallel filaments, and thus a gravity dominated HFS can be formed. Star formation could be triggered when the thermally supercritical main filament form during (c)–(e), and cluster formation may occur inside HFS. (f) If the main filament or HFS is massive enough to form OB stars, the massive YSOs would produce HII regions and the the expansion fronts could further compress nearby material and form compressed filaments.

6. SUMMARY AND CONCLUSION

We performed optical and infrared polarization observations toward background stars seen through IC5146 molecular cloud using AIMPOL in ARIES observatory, TRIPOL in Lulin observatory and Mimir in Lowell observatory. We obtain more than 2000 polarization
detections over the $A_V < 20$ mag region. We measured the gas kinematics in several regions with CO using ARO 12M telescope and $^{13}$CO using CSO 10.4M telescope. Combination of our polarization data and the Herschel images reveal interaction between B-field and the cloud. From the analysis of these data, we came to the following conclusions

1. The dust polarization efficiency ($P_\lambda/\tau_K$) derived from our $R_c$, H and K data decrease with $A_V$ by power-law indices of $-0.97 \pm 0.03$, $-0.52 \pm 0.02$ and $-0.58 \pm 0.09$, respectively. The strong dependency is consistent with RATs dust alignment model, suggesting the polarizations are tracing the magnetically aligned dust. In addition, our detections go beyond $A_V \gtrsim 10$ mag where Whittet et al. (2008) predict the efficiency should approach to zero, and show that the observed polarization can trace the B-field up to at least $A_V$ 20 mag.

2. We find a broken power-law relation between polarization efficiency and $A_V$ with a break point of $\sim 3$ mag. Our normalization analysis suggest that this relation is more likely due to the change of dust properties instead of the survival radiation due to the extinction. The break point is similar to the extinction threshold for formation of $H_2O$-ice formation (Chiar et al. 2011), implying that the formation of the ice mantles on dust grains may directly change the dust alignment efficiency.

3. Our polarization measurements reveal a mostly ordered B-field perpendicular to main filament in large scale, suggesting that the evolution of the cloud is likely regulated by strong B-field. The nearby sub-filaments are parallel to B-field and have a velocity gradient along B-field detected by CO, suggesting they are possibly the mass flows accumulated toward main filament.

4. We estimate the B-field strength over IC5146 based on Chandrasekhar-Fermi method. The B-strength v.s. density plot shows a power-law scaling with an index of $0.52\pm0.02$,
and the low density regions \( n_H \lesssim 5000 \text{cm}^{-3} \) are magnetically subcritical whereas the high density regions are supercritical. It suggests that the B-field is dynamically important for the cloud evolution, and the tight power-law correlation suggest that the magnetic flux may be removed smoothly from magnetically subcritical clouds.

5. Our polarization measurements favor the strong B-field model (e.g. Nakamura & Li 2008; Inutsuka et al. 2015) in most of the regions. The ordered large scale B-field aligned to filament does not appear to support the turbulence or gravity dominated models (e.g. Padaon et al. 2001; Gómez & Vázquez-Semadeni 2014) in large scale. However, the gravity dominated models are likely valid near the Hub-filament structures and the shock dominated model possibly work near the Cocoon Nebula.

6. We propose to classify the filaments in IC5146 into four types: (1) main filament is the spines of the large scale filament perpendicular to B-field, (2) Accretion filament is the accretion flow along B-field, (3) Hub-filament system is a dense hub where filaments converged, and (4) Compressed filament is originated from compression of shock. The B-field is dynamically important in first two types whereas the gravity and shock dominate the last two types, respectively. These examples show that the filamentary structures we observed can be possibly generated from diverse mechanisms even in the same cloud.

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A. A. Data Consistency

To examine if the results from AIMPOL, TRIPOL and Mimir are consistent, we select those stars with detections in multi-wavelength, and examine whether their P.A.s is consistent in different wavelength in Figure 21. The standard deviations of the difference in P.A.s are 15°, 17°, and 26° for $R_c$-H, $R_c$-i’, and H-K, respectively. The typical uncertainty of P.A. for $R_c$ and i’ data is $\sim$ 5 deg and for H and K is $\sim$ 10 deg. The propagated uncertainty for $P.A._{R_c-i'}$, $P.A._{R_c-H}$, and $P.A._{H-K}$ is $\sim$ 7 deg, $\sim$ 11 deg, and $\sim$ 14 deg, respectively. The standard deviation obtained from these star sets is thus $\sim$ 1 – 2 observational uncertainty ($\sigma$), which is an acceptable value since the P.A. in different wavelength may be intrinsically different because they may trace the polarization in different depth. We note that $\sim$0%, $\sim$1%, and $\sim$10% of samples are larger than 3$\sigma$ for $P.A._{R_c-i'}$, $P.A._{R_c-H}$, and $P.A._{H-K}$, respectively. These percentages suggest that the K polarizations are noisier than measurements in other wavelengths; nevertheless, 90% of the K polarization measurements are still reliable.
B. B. Sensitivity for Polarization Measurements in Multi-wavelength

Optical and infrared polarizations are two common methods to measure the B-field in particular extinction range. The infrared radiation is much easier to penetrate the dense cloud; however, it also has a lower polarization efficiency. In this section, we show a quantitatively description for how adaptable the wavelength is to measure the polarization in particular extinction range. The S/N ratio of polarized flux from a background stars measured with an instrument can be described as:

\[
(S/N)_{\text{pol}} = (S/N)_{\text{flux}} \times \text{Polarization(\%)}
\]  

(B1)

where \( S/N_{\text{flux}} \) is the S/N for the total flux of a source. Using a simple extinction law, the \( (S/N)_{\text{flux}} \) can be further expressed as \( (S/N)_{\text{int}} \times 10^{-0.4C_{\text{ext,\lambda}} \times A_V} \), where \( (S/N)_{\text{int}} \) is the S/N for the intrinsic flux of a background star without extinction. The polarization can also be expressed as function of \( A_V \) by a empirical simple power-law as describe in Figure 4. Therefore, we can rewrite the S/N of final polarization as:

\[
(S/N)_{\text{pol}} = (S/N)_{\text{int}} \times 10^{-0.4C_{\text{ext,\lambda}} A_V} \times P(A_V, \lambda)
\]  

(B2)

Here \( P(A_V, \lambda) \) is determined by the dust polarization efficiency, which can be obtained from the fitting of our data (Figure 4). The equation shows that the instrumental sensitivity and brightness of background stars only linearly scale the \( (S/N)_{\text{pol}} \) curve, and the slope of the curve is determined only by the extinction law and declination of polarization efficiency.

Figure 22 shows the observed \( (S/N)_{\text{pol}} \) for our samples and the prediction from Equation B2. The observed \( (S/N)_{\text{pol}} \) in \( R_c \)- and \( i' \)-band is higher than H- and K-band in \( A_V \lesssim 5 \text{mag} \) regime but drops significantly when \( A_V > 5 \text{mag} \). The predicted sensitivities of \( R_c, i', H, \) and K- bands are peaked at \( A_V = 0.4, 0.6, 2.6, \) and \( 3.8 \text{ mag} \), respectively. Since the observed background stars have diverse brightness, we only roughly scale the peak \( (S/N)_{\text{pol}} \) from detections to the maximum observed \( (S/N)_{\text{pol}} \). The plot shows that
the optical polarization can reach very high S/N in low extinction range \((A_V \leq 5)\) but drop significantly due to extinction effect and steeply decreasing polarization efficiency. The H and K polarization provide lower S/N than optical in \((A_V \leq 5)\) as a result of lower sensitivity and polarization efficiency, but can keep measurable until \(A_V \sim 25\) in advantage of the less effect of extinctions. In addition, even though the S/N peak of K polarization is at higher \(A_V\) than H polarization, the K band data always provide lower or similar S/N than H band due to lower sensitivity. Based on these analysis, we suggest that the optical polarimetry is more adaptable to measure the magnetic field in \(A_V \leq 5\), while the infrared polarimetry will be better to trace the magnetic field in \(A_V > 5\) mag region. Furthermore, H polarimetry is likely more efficient than K polarimetry in most observable extinction range \(A_V < 25\). We note that the correlation we shown here depends on the dust polarization efficiency, which is possibly vary due to the different dust property or alignment condition and thus could be different from cloud to cloud (Whittet et al. 2008; Alves et al. 2014; Cashman & Clemens 2014).
Fig. 1.— The fields surveyed in our polarization observations overlaid on Herschel 250 µm image. The fields observed with TRIPOL, AIMPOL, Mimir, ARO, and CSO are labeled with white boxes, green circles, blue boxes, magenta boxes, and blue boxes, respectively. The yellow dashed lines denotes the sub-region discussed in this paper.
Fig. 2.— The polarization map of IC5146 overlaid on Herschel 250 μm image. (a) The detections in TRIPOL i'-band, AIMPOL Rc-band, Mimir H- and K-band are labeled with white, green, cyan, and magenta. (b) The comparison of P.A. between PLANCK 353GHz results and our data. The blue vectors show the P.A. of PLANCK 353 GHz polarization with a spatial resolution of 5′. The green vectors show the P.A. from all of our optical and
Fig. 3.— Histogram of NICE $A_V$ for all our detections. The detections are mostly distributed in $A_V < 5$ mag and the detection limit is $A_V \sim 23$ mag.

Table 1. The $R_c$-band Polarization Data

| Star Number | $\alpha$ (J2000) | $\delta$ (J2000) | P (%) | $\sigma_P$ (%) | PA (deg) | $\sigma_{PA}$ (deg) | J (mag) | H (mag) | K (mag) |
|-------------|------------------|------------------|-------|----------------|----------|----------------------|--------|--------|--------|
| 1           | 326.040102       | 47.703938        | 1.71  | 0.08           | 24.5     | 1.1                  | 10.299 | 10.128 | 10.053 |
| 2           | 326.049416       | 47.702999        | 1.84  | 0.35           | 24.7     | 4.7                  | 13.018 | 12.590 | 12.508 |
| 3           | 326.051165       | 47.729969        | 1.45  | 0.30           | 122.3    | 4.9                  | 13.104 | 12.823 | 12.726 |
| 4           | 326.053245       | 47.698971        | 1.26  | 0.13           | 14.1     | 2.4                  | 8.329  | 7.247  | 6.838  |
| 5           | 326.058284       | 47.740124        | 1.45  | 0.22           | 29.2     | 3.6                  | 12.564 | 12.221 | 12.149 |

Note. —
(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Fig. 4.— The polarization efficiency versus $A_V$ at different wavelength. The plot of $R_c$-, H- and K-band are shown in the (a), (b), and (c) pannel, respectively. The black points show the averaged data in the bins with width of $\log A_V = 0.2$. The averaged data are fitted with a single power-law, and the solid line indicates the best fit.
Fig. 5.— The polarization efficiency versus $A_V$ for H-band data, grouped based on $A_V$. The group with $A_V < 3$ and $A_V > 3$ are shown in red and green. The two groups are fitted with a simple power-law separately, and the solid lines indicate the best fit. The fitting results indicate the correlation is more like a broken power-law, steep in low $A_V$ but flat in high $A_V$, instead of one single power-law.
Fig. 6.— The dependence of polarization degree on wavelength. The diagrams show polarization percentage of each star detected at both wavelengths. The correlation are fitted with a single power-law, and the dashed line indicates the best fit.

Table 2. The i'-band Polarization Data

| Star Number | α       | δ       | P      | σ_P    | PA     | σ_PA   | J      | H      | K      |
|-------------|---------|---------|--------|--------|--------|--------|--------|--------|--------|
|             | (J2000) | (J2000) | (%)    | (%)    | (deg)  | (deg)  | (mag)  | (mag)  | (mag)  |
| 1           | 326.329633 | 47.696457 | 2.24   | 0.55   | 83.9   | 7.0    | 15.073 | 14.441 | 14.065 |
| 2           | 326.334933 | 47.670689 | 0.57   | 0.05   | 33.5   | 2.3    | 12.081 | 11.745 | 11.686 |
| 3           | 326.338354 | 47.696922 | 6.61   | 0.49   | 40.8   | 2.1    | 15.799 | 15.167 | 15.070 |
| 4           | 326.339392 | 47.700027 | 1.67   | 0.55   | 36.1   | 9.5    | 15.608 | 14.983 | 14.869 |
| 5           | 326.340876 | 47.633430 | 1.20   | 0.09   | 39.6   | 2.2    | 13.325 | 12.973 | 12.862 |

Note. —

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Fig. 7.— (a) The polarization efficiency versus $A_V$ at multi-wavelength. (b) The comparison of the normalized polarization efficiency at multi-wavelength. The polarization percentage at different wavelengths are normalized to H-band using the correlation shown in Fig. 7.
Fig. 8.— The field 1–3 for our $CO$ J=1-0 line observations with ARO 12M telescope, and the field 4 for the $^{13}CO$ J=3-2 line observation. The background is Herschel 250 µm image and the color scale is the same for three panels.
Fig. 9.— (a) The integrated intensity contour overlaid on averaged velocity map for field 1. Our polarization measurements are shown in magenta. (b) The position-velocity plot along the red line, indicating a velocity gradient of $0.6 \text{ km s}^{-1} \text{ pc}^{-1}$. 
Fig. 10.— Same as Fig. 9, but for field 2. The red line roughly labels the boundary between the main filament and the sub-filament. Significant velocity gradient is shown only in the sub-filament region.
Fig. 11.— Same as Fig. 9, but for field 3. The velocity split into two peaks in the northern part possibly due to clump expansion (red box), and the blue line labels the velocity gradient.
Table 3. The H-band Polarization Data

| Star Number | \(\alpha\) (J2000) | \(\delta\) (J2000) | \(P\) (%) | \(\sigma_P\) (%) | \(PA\) (deg) | \(\sigma_{PA}\) (deg) | \(J\) (mag) | \(H\) (mag) | \(K\) (mag) |
|-------------|--------------------|--------------------|----------|----------------|-------------|----------------|-----------|-----------|-----------|
| 1           | 325.743854         | 47.820540          | 2.09     | 1.00           | 67.9        | 13.7           | 13.712    | 13.086    | 12.863    |
| 2           | 325.748713         | 47.691497          | 0.43     | 0.16           | 171.3       | 10.6           | 11.302    | 10.626    | 10.426    |
| 3           | 325.762890         | 47.888979          | 0.83     | 0.22           | 10.7        | 7.7            | 10.898    | 10.234    | 10.076    |
| 4           | 325.768709         | 47.725315          | 0.81     | 0.24           | 169.3       | 8.3            | 11.756    | 11.095    | 10.927    |
| 5           | 325.770907         | 47.721085          | 0.77     | 0.12           | 178.8       | 4.5            | 10.796    | 10.131    | 9.950     |

Note. —
(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Table 4. The K-band Polarization Data

| Star Number | $\alpha$ (J2000) | $\delta$ (J2000) | P (%) | $\sigma_P$ (%) | PA (deg) | $\sigma_{PA}$ (deg) | J (mag) | H (mag) | K (mag) |
|-------------|------------------|------------------|-------|---------------|----------|----------------------|---------|---------|--------|
| 1           | 326.196443       | 47.639951        | 0.87  | 0.36          | 142.5    | 11.8                 | 11.933  | 10.798  | 10.385 |
| 2           | 326.205915       | 47.610243        | 3.01  | 0.91          | 1.4      | 8.7                  | 15.705  | 12.995  | 11.751 |
| 3           | 326.217027       | 47.633045        | 3.87  | 1.86          | 154.6    | 13.8                 | 15.061  | 13.455  | 12.681 |
| 4           | 326.231492       | 47.575286        | 2.37  | 0.98          | 175.2    | 11.8                 | 13.346  | 12.274  | 11.884 |
| 5           | 326.262829       | 47.549705        | 1.03  | 0.49          | 89.0     | 13.8                 | 11.155  | 10.971  | 10.934 |

Note. —
(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Fig. 12.— (a) $^{13}\text{CO}$ J=2-1 emission toward The Western Part of main filament. Redshifted $^{13}\text{CO}$ J=2-1 emission integrated from $V_{LSR} = 3.5\text{km/s}$ to $5\text{km/s}$ is shown as red and the blueshifted component integrated from $V_{LSR} = 2\text{km/s}$ to $3.5\text{km/s}$ is shown as blue. Yellow vectors are our poalrization data. (b) The average spectrum over the whole field. The blue line indicate the boundry of the two component shown in left panel.
Fig. 13.— (a) The Gaussian smoothed B-field strength map based on Chandrasekhar-Fermi method. The color beams only label the positions of our estimations, and the real beams
Fig. 14.— B-field strength versus hydrogen volume density. The data points are obtained from averaging all measurements within a 7 arcmin bin around each star. If the correct distance of IC5146 is 950 pc instead of 460 pc, each point will shift along the direction of the black vector. The blue line is the best fit using a single power-law with a scaling index of 0.52 ± 0.02. The green and black line label the critical mass-to-flux ratio assuming a thickness of 0.1 pc for D=460 pc and a thickness of 0.2 pc for D=950 pc. The magenta line denotes the maximum B-field strength estimated in Crutcher (2012).
Fig. 15.— (a) The zoom-in of Fig. 2 toward The Cocoon nebula. The color scale is reset to emphasize the filaments high density region, and the contour represents the column density ($N_{H_2}$) starting from $0.5 \times 10^{21} \text{cm}^{-3}$ to $5 \times 10^{21} \text{cm}^{-3}$ with a step of $0.5 \times 10^{21} \text{cm}^{-3}$, and a step of $2.5 \times 10^{21} \text{cm}^{-3}$ after $n_{H_2} > 5 \times 10^{21} \text{cm}^{-3}$. The yellow star labels the B0 V star BD $+46^\circ3474$. (b) The Histogram of P.A. in the region, and the dashed line shows the average P.A.
Fig. 16.— (a) The zoom-in of Fig. 2 toward the eastern part of main filament. The green line represents the orientation of the main filament selected by eyes. (b) The Histogram of P.A. for the samples in the yellow box. The dashed lines show the average of the two component, and the green and blue lines label the P.A. parallel and perpendicular to the main filament, respectively. (c) The variation of P.A. along the main filament. The x axis denotes the projection distance of polarization detections along the filament and the 0 position is defined as the east-end of the green line.
Fig. 17.— Investigation of the difference in $A_V$, polarization degree, polarization efficiency and color-color diagram between the two components shown in Fig. 16. The normalized histogram of $A_V$ and polarization degree are plotted in (a) and (b), where green and blue denotes the minor and major components. The (c) and (d) show polarization efficiency vs. $A_V$ and the J-H vs. H-K plots, respectively, where the minor and major components are colored with green and blue. The red and blue lines in polarization efficiency vs. $A_V$ plot are the best fit for all clouds shown in Fig. 5. The red points in color-color diagram label the intrinsic color of main-sequence stars (Koornneef 1983).
Fig. 18.— (a) The zoom-in of Fig. 2 toward The western part of main filament. The yellow boxes denote the hub-filament structure and the green line represents the orientation of the main filament selected by eyes. (b) The Histogram of P.A. for the samples in the white box. The dashed lines show the average P.A., and the green and blue lines label the P.A. parallel and perpendicular to the main filament, respectively. (c) The variation of P.A. along the main filament. The red and black points show the samples in the white and black boxes respectively. The x axis denotes the projection distance of polarization detections along the filament and the 0 position is defined as the east-end of the green line.
Fig. 19.— (a) The zoom-in of Fig. 2 toward the northern region. The teal and green lines indicate the orientation of the filament N1 and N2. (b) The Histogram of P.A. for the samples in the blue, green and teal boxes. The dashed lines show the average P.A. of the three groups. (c) The variation of P.A. along the filament N2. The teal and green points are the detections near filament N1 and N2. The solid and dash lines show the P.A. parallel and perpendicular to the filament N1 (teal) and N2 (green). The x axis denotes the projection distance of polarization detections along the filament and the 0 position is defined as the north-end of the filament N1 and N2.
Fig. 20.— Possible scenarios for the evolution of the four types of filaments. (a) Main filament generated due to contraction along B-field. (b) Gas near the main filament is still flowing along B-field as accretion filaments. (c) Main filament gradually become thermally supercritical. (d) Thermally supercritical filament fragment along B-field and produce sub-filaments with similar orientations. (e) The sub-filaments merge into a dense hub, and the material in the surrounding filaments is accreting toward the hub. The accretion flows further drag and disorder the local B-field. (f) If a massive star form inside the hub region, the HII bubble may compress nearby material and B-field, and the compressed shell evolves to second generation filaments.
Fig. 21.— Examination of data consistency via the data from the common stars. The common stars observed with at least two instruments are selected, and their difference of P.A. are shown in the histogram. The comparison between R- and H-band, $R_c$- and $i'$-band, and H- and K-band are shown in top, middle, and bottom panel, respectively.

Fig. 22.— The signal-to-noise ratio of polarization percentage detections ($S/N_{\text{Polarization}}$) versus $A_V$ using different instruments. The data from AIMPOL, TRIPOL, Mimir H-band and Mimir K-band data are shown in purple, red, light blue, and black, respectively. The solid lines indicate the tendency derived from Eq B2 and scaled to the peak of each data sets.
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