Magnetic fields in star forming systems (I): Idealized synthetic signatures of dust polarization and Zeeman splitting in filaments

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ABSTRACT
We use the POLARIS radiative transport code to generate predictions of the two main observables directly sensitive to the magnetic field morphology and strength in filaments: dust polarization and gas Zeeman line splitting. We simulate generic gas filaments with power-law density profiles assuming two density-field strength dependencies, six different filament inclinations, and nine distinct magnetic field morphologies, including helical, toroidal, and warped magnetic field geometries. We present idealized spatially resolved dust polarization and Zeeman-derived field strengths and directions maps. Under the assumption that dust grains are aligned by radiative torques (RATs), dust polarization traces the projected plane-of-the-sky magnetic field morphology. Zeeman line splitting delivers simultaneously the intensity-weighted line-of-sight field strength and direction. We show that linear dust polarization alone is unable to uniquely constrain the 3D field morphology. We demonstrate that these ambiguities are ameliorated or resolved with the addition of the Zeeman directional information. Thus, observations of both the dust polarization and Zeeman splitting together provide the most promising means for obtaining constraints of the 3D magnetic field configuration. We find that the Zeeman-derived field strengths are at least a factor of a few below the input field strengths due to line-of-sight averaging through the filament density gradient. Future observations of both dust polarization and Zeeman splitting are essential for gaining insights into the role of magnetic fields in star and cluster forming filaments.

Key words: magnetic fields radiative transfer methods: numerical techniques: polarimetric techniques: spectroscopic stars: formation ISM: magnetic fields ISM: structure infrared: ISM submillimetre: ISM

1 INTRODUCTION
The study of gas filaments has virtually exploded in the field of star and cluster formation in the last ∼ half decade. This explosion has been predominately driven by data from the Herschel satellite, which showed with more undeniable empirical clarity than previously available that main structural components of star-forming molecular clouds are filaments (e.g., Molinari et al. 2010; André et al. 2010; Rathborne et al. 2011; Arzoumanian et al. 2011; Stutz & Kainulainen 2015; Stutz & Gould 2016). At the same time, driven by the observational basis provided most recently by the Planck mission (Tauber et al. 2010; Planck Collaboration et al. 2011), the study of the observational signatures of the magnetic field with polarization is receiving renewed and heated interest in these filamentary star forming regions. While the Planck data have comparatively low angular resolution, their contribution to the discussion of filament structure through dust polarization observations is undeniable (Planck Collaboration et al. 2015, 2016a). ALMA mosaic observations will be

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able to probe more distant and massive filaments throughout the Galaxy using both (sub)millimeter dust polarization and Zeeman line splitting observation. Already a variety of single dish results have paved the way for such observations (e.g., Matthews et al. 2001, 2002; Bertrang et al. 2014; Pillai et al. 2015; Pattie et al. 2017).

On the theoretical side, a wealth of studies going back to Chandrasekhar & Fermi (1953) have explored the possible roles of magnetic fields in combination with turbulence in the ISM and specifically in filaments (e.g. Nagasawa 1987; Fiege & Pudritz 2000a; Tomisaka 2014; Toci & Galli 2015a; Schleicher & Stutz 2018). The advent of improved turbulence simulations (e.g., Chen & Ostriker 2015; Walsh et al. 2015; Seifried et al. 2017; Ibáñez-Mejía et al. 2017; Normoussi et al. 2017; Illfig & Hennebelle 2017; Inoue et al. 2017) with the inclusion, if in a simplified fashion, of magnetic fields in the form of an additional source of pressure in the gas have further driven forward the study of the possible role of magnetic fields in such structures in the ISM. In these works, various scenarios have been proposed, as well as various field configurations, both on the basis of direct observations (which have in the past been comparatively limited) and on the basis of what is “observed” in the numerical simulations (see Klessen & Glover 2016, for review).

The main configurations that have been proposed and observed for magnetic field geometries can be divided into two principle categories illustrated in Figure 1. First, there are those that represent distortions of an approximately straight field-line configuration, such as a bow-like or a gravitationally distorted field. Then there are those that are entirely curved and have dissolved (or approximately closed and approximately divergence free) field lines, such as a toroidal or helical field configuration wrapping around the filament (e.g., Heiles 1987; Uchida et al. 1991; Tatamatsu et al. 1993; Heiles 1997; Fiege & Pudritz 2000a; Schleicher & Stutz 2018; Tahani et al. 2018). We expect potentially radically different behaviors of a system in the presence of these two different types of fields. For example, for a helical field we might observe a magnetic pinch (so called “z-pinches”; e.g., Bocchi et al. 2013; Slentz & Mond 2009) instability to develop, which may compress the filament material (Stutz & Gould 2016; Stutz 2018). In the presence of a bow shaped field, the interpretation of the observed geometry may lead to the conclusion that a field is being distorted by the action of gravity and the magnetic field is energetically sub-dominant. Both are in principle possible or at least have been previously proposed, yet the consequences and implications for filamentary star and cluster formation may be very different in each case.

In order to constrain possible underlying field configurations, synthetic observations are an essential intermediate step in the analysis of actual observations. Here we focus on two observable signatures of the magnetic field: dust polarization (see Andersson et al. 2015, for a review) and Zeeman splitting of various molecular lines (e.g., Crutcher et al. 1993). We adopt a filament power-law density profile consistent with observations of the Orion A Integral Shaped Filament (ISF; Stutz & Gould (2016)) and also test other density profiles (e.g., Arzoumanian et al. 2011). As for our adopted magnetic field configurations we implement numerous suggestions from observations and theoretical works, focusing on five distinct magnetic field morphologies associated with the evolution of filaments and star formation. We then predict their idealized observable signatures by making use of the radiative transfer (RT) code POLARIS (Reissl et al. 2016; Brauer et al. 2017). The POLARIS code is the first of its kind capable of simulating dust polarization on the basis of state of the art grain alignment physics in combination with line RT, including the Zeeman effect. From the dust polarization signature we obtain the 2D projections of the magnetic field in the plane of the sky ($B_z$), under the assumption that the dust grains are aligned by radiative torques (RAT; Draine & Weingartner 1996, 1997; Weingartner & Draine 2003; Lazarian & Hoang 2007, which is the most likely cause of grain alignment). From the Zeeman line splitting signature we obtain two pieces of information: the line-of-sight (LOS) component of the magnetic field strength (estimated from simulated circular polarization profile). This synthetic observation approach is the first to predict the impact of the magnetic field morphology on the dust polarization pattern and the complementary Zeeman measurements simultaneously. The combination of these two diagnostics will prove to be invaluable in the ultimate goal of reconstructing the 3D magnetic field configuration in the future when both types of observations become routine in star and cluster forming filaments.

We demonstrate in this paper that dust polarization alone provides ambiguous constraints for the magnetic field morphology. We show that Zeeman observations provide the necessary additional information to constrain the underlying 3D magnetic field morphology.

This paper is organized as follows: First, we introduce the geometry, gas density profile, and velocity profile of our filament model in Sect. 2.1. Then, we give a description of the applied dust component in Sect. 2.2 followed by the modeling parameters of the magnetic field morphologies that we consider in Sect. 2.3. In Sect. 3.1 we present a way of synthesizing additional molecular abundances. The physics of dust heating and grain alignment, as well as RT with polarized radiation, is introduced in Sect. 3.2 followed by the method of deriving synthetic Zeeman observations in Sect. 3.3. We discuss the resulting dust polarization pattern and LOS magnetic field profiles in Sect. 4.1 and Sect. 4.4, respectively. Finally, we summarize our results in § 5.

## 2 FILAMENT MODELING

### 2.1 Radial density and velocity profiles

Our idealized filament is modeled as a cylinder of infinite length with its symmetry axis along the y-axis of the coordinate system (see Fig. 1). Calculations are carried out within a cube with a side length of 10 pc for all models. For simplicity, the profiles of density and velocity are parametrized by the dimensionless cylindrical radius,

$$|r_{cyt}| = \frac{1}{10 \, \text{pc}} \sqrt{x^2 + z^2},$$

normalized to the length of the model.

We assume a radially symmetrical volume density distribution consistent with Stutz & Gould (2016) volume density profile derived from column density observations. We

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Magnetic fields in filaments (I)

Figure 1. Panel a: Model cube with a side length of ±10 pc. The isosurface represents the gas number density $n_{gas}(r_{cyl})$ (see Eq. 2) at a distance of $r_{cyl} = 0.25$ and $r_{cyl} = 1$, respectively, from the symmetry axis. The red arrows indicate the orientation of the velocity field of the slightly collapsing filament, while the black dashed lines indicates the observer plane along which all synthetic observations are derived. The direction of observation is by default along the z-axis while all rotations are performed around the x-axis. Panel b: The magnetic field model 'toro' modeled with Eq. 6. Panel c: Representation of the class of helical magnetic field model 'heli', modeled with Eq. 7 shown for a pitch angle of $\alpha = 45^\circ$. Panel d: The magnetic field model 'cont' modeled with Eq. 8. Red arrows indicate the velocity components of the velocity field presented in panel a, that can drag the magnetic field lines. Panel e: The magnetic field model 'cont' modeled with Eq. 9. The red arrow indicates the contraction of the filament along the symmetry axis. Panel f: The magnetic field model 'flow' modeled with Eq. 10. The red arrows indicate the additional velocity component with which the filament is drifting into the initially straight magnetic field morphology.

adopt the Plummer power-law profile as suggested in Plummer (1911):

$$n_{gas}(r_{cyl}) = n_0 \left[1 + \left(\frac{r_{cyl}}{r_{flat}}\right)^2\right]^{-\beta}.$$  

Here, $r_{flat}$ defines the characteristic radius of the density profile close to the center of the filament where the profile becomes flat and the parameter $\beta$ controls the slope of the density at the outer regions. We apply a typical value in the order of $r_{flat} = 0.05$, consistent with Palmeirim et al. (2013), but see also Smith et al. (2014, 2016); Boekholt et al. (2017) for the inference of a much smaller filament volume density profile inner softening scale. Although this Plummer profile differs from the density profile presented in Arzoumanian et al. (2011) close to the center we use their average value of $\beta = 1.6$ as a starting point, which is consistent with observations in the Integral Shaped Filement (ISF) in Orion (Stutz & Gould 2016), as mentioned above and so we restrict our analysis here to this alignment mechanism. In order to investigate the possible influence of different density profiles we consider a range values of $\beta \in [1.6 : 2]$. The central number density $n_0$ is chosen to keep the total mass $M_{tot}$ of the filament within the cube at a typical value of $M_{tot} = 31000 M_\odot$ for all parameters of $\beta$, comparable to the mass observed in the high line mass ISF (Stutz & Gould 2016).

We take that the filament is slowly contracting toward its axis of symmetry (see Figure 1 with a velocity field defined by:

$$\vec{v}_{rad}(r_{cyl}) = -\frac{5000}{\sqrt{x^2 + z^2}} \left( x, 0, z \right) \text{[m/s]}.$$  

We apply the same velocity field for all of our models if not explicitly stated otherwise. For the line RT calculations performed in the following sections we assume additionally a turbulent velocity component of $v_{turb} = 200$ m/s. The magnitude of both velocities is chosen to be in agreement with Eq. 3 shown for a pitch angle of $\alpha = 45^\circ$. Panel d: The magnetic field model 'cont' modeled with Eq. 8. Red arrows indicate the velocity components of the velocity field presented in panel a, that can drag the magnetic field lines. Panel e: The magnetic field model 'cont' modeled with Eq. 9. The red arrow indicates the contraction of the filament along the symmetry axis. Panel f: The magnetic field model 'flow' modeled with Eq. 10. The red arrows indicate the additional velocity component with which the filament is drifting into the initially straight magnetic field morphology.
Figure 2. Left panel: Sketch of aligned dust grains precessing with their angular momentum \( \vec{J} \) (red arrows) around the magnetic field direction \( \vec{B} \) (blue arrows) observed along the LOS (black dashed arrows). In scenario (A) \( \vec{B} \) and LOS are parallel and the dust grains appear spherical. Hence, no linear \( P_l \) or \( P_c \) polarization can be observed. Scenario (B) shows twisted field lines. The net orientation of linear polarization \( P_l \) represents a superposition of all the field lines along the LOS and a small amount of circular polarization \( P_c \) accumulates. In scenario (C) are all adjacent field lines parallel to each other. The linear polarization \( P_l \) is maximal while all polarized radiation experiences the same amount of differential phase lag. Consequently, no circular polarization \( P_c \) can be built up. In case (D) two adjacent field lines are exactly perpendicular to each other. All contributions of polarized thermal dust emission cancel out. Right: Sketch of Zeeman observations along different LOS directions for the case of a toroidal magnetic field morphology \( \vec{B} \). When LOS and \( \vec{B} \) are perpendicular, the magnetic field component \( \vec{B}_{||} \) can be observed. For a LOS that is parallel or anti-parallel, respectively, to \( \vec{B} \), the component \( \vec{B}_{||} \) has its maximum. The sign of \( \vec{B}_{||} \) allows us to infer the parallel or anti-parallel configuration of \( \vec{B} \) with respect to the LOS.

Figure 3. Left panel: Radial gas temperature \( T_{\text{gas}} \) distribution (purple) and dust temperature \( T_{\text{dust}} \) distribution (red) for a density slope index of \( \beta = 1.6 \) (solid) and \( \beta = 2.0 \) (dashed). Right panel: Corresponding radial number densities for the molecular species considered here: \( \text{H}_2 \) (red), HI (purple), OH (yellow), CN (green), and SO (blue) for \( \beta = 1.6 \) (solid) and \( \beta = 2.0 \) (dashed). This figure illustrates that the parameters show above have only a weak dependence on the density profile power law index in Eqn. 2.

with observations (e.g. García-Díaz & Henney 2007; Arthur et al. 2016).

2.2 Dust grain properties

We assume dust grains to be oblate spheroids with an aspect ratio of 0.5 (Hildebrand et al. 1995; Draine & Hensley 2017). The grain size is characterized by an effective radius \( a_{\text{eff}} \) of a sphere of equivalent volume. As presented in Mathis et al. (1977), see also Weingartner & Draine (2000) for the size distribution we apply

\[
n(a_{\text{eff}}) \propto a_{\text{eff}}^{-3.5}
\]

and consider a mixture of materials of 37.5% graphite and 62.5% amorphous silicate grains that is consistent with the best fit model of the extinction curve of our own galaxy (Mathis et al. 1977). Although larger grain sizes may grow in filaments, we fix the size distribution with sharp upper and lower cut-offs at the \( a_{\text{low}} = 5 \) nm and \( a_{\text{up}} = 250 \) nm, respectively, typical for the ISM. We apply the usual ratio of \( m_{\text{dust}}/m_{\text{gas}} = 0.01 \) for the dust mass to gas mass ratio (Mathis et al. 1977; Boulanger et al. 2000). A dust model with larger grains would lead to an increase in intensity but a decrease in polarization (Reissl et al. 2017). The cross sections for extinction \( C_{\text{ext}, \lambda} \) and emission \( C_{\text{abs}, \lambda} \) are pre-
calculated values utilizing the scattering code DDSCAT\textsuperscript{2} v7.3.2 (Draine \& Flatau 2013) for 100 size bins and 104 wavelength bins in the range of $\lambda \in [0.9 \mu m : 3 \mu m]$ (see Reissel et al. 2017, for details). As input of the code we consider the optical properties of the differently materials presented by Lee \& Draine (1985) and Laor \& Draine (1993). In this paper we take use of the approximation of the efficiency factor,

$$Q_\Gamma = \begin{cases} 
0.4 & \text{if } \frac{\lambda}{\lambda_{\text{eff}}} \leq 2 \\
0.4 \left(\frac{\lambda}{\lambda_{\text{eff}}}\right)^{-3} & \text{if } \frac{\lambda}{\lambda_{\text{eff}}} > 2
\end{cases}$$

(5)

that quantifies the efficiency of the dust grains to spin up when exposed to an external an-isotropic radiation field (see Lazarian \& Hoang 2007; Hoang \& Lazarian 2014).

2.3 Magnetic field morphologies

Several models have been proposed over the years arguing for the stability and shape of filaments on the basis of linear polarization.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Synthetic dust polarization quantities for the considered magnetic field morphologies observed at a wavelength of $\lambda = 500 \mu m$. Different colors indicate results for different filament inclination angles $i \in [0^\circ, 75^\circ]$ in steps of 15$^\circ$ as indicated by different colors, where $i = 0^\circ$ corresponds to viewing angle perpendicular to the filament axis. Left column: normalized orientation of linear polarization pseudo-vectors along a cut perpendicular to the filament axis (in the "observer plane", see black dashed lines in panel a. of Fig. 1). Middle column: degree of linear polarization as a function of projected radius. Right column: degree of circular polarization; dashed lines represent the negative values of circular polarization, i.e., a flip in the inferred LOS field direction.}
\end{figure}
of toroidal or helical fields (e.g., Nagasawa 1987; Fiege & Pudritz 2000a; Toci & Galli 2015b). However, observational constraints by means of either dust polarization or Zeeman measurements for such fields have been difficult to interpret (e.g., Heiles 1997; Falgarone et al. 2001; Palmeirim et al. 2013). Hence, we model a purely toroidal by an analytic expression with

$$\vec{B}(\vec{r}_{\text{cyl}}) = \frac{B_0(\vec{r}_{\text{cyl}})}{\sqrt{x^2 + z^2}} (-z, 0, x)^T,$$  

(6)
Magnetic fields in filaments (I) 7

Figure 6. Left panel: Radial distances of the flipping point of the orientation of linear polarization as a function of inclination $i$ for the toroidal field model (‘toro’) for different observed wavelengths $\lambda$ as well as different assumed density profile power law indices ($\beta$). Right panel: The same as the right panel for the model ‘cont’.

Figure 7. Left panel: The same as Fig. 6 for the model ‘heli'$_{cyl}$ with a fixed pitch angle of $\alpha = 45\degree$ and an inclination $i \in [3\degree, 87\degree]$. Right panel: Radial distance of the flipping points for the class of helical models ‘heli’$_{cyl}$ as a function of pitch angle $\alpha$ for a fixed inclination of $i = 0\degree$.

where $B_0(r_{cyl})$ is a function accounting for the radial magnetic field strength (see below) and the superscript $T$ stands for a transposed vector. We label this kind of model as ‘toro’ in the following sections. However, a purely toroidal field is just a special case in the much broader class of helical fields. Helical magnetic fields can conveniently be modeled by

$$B(\vec{r}_{cyl}) = B_0(\vec{r}_{cyl}) \left( -z \cos(\alpha)/\sqrt{x^2 + z^2}, \sin(\alpha), x \cos(\alpha)/\sqrt{x^2 + z^2} \right)^T. \tag{7}$$

Here, $\alpha$ is the pitch-angle of the field where $\alpha = 0\degree$ represents the toroidal case above. We refer to this class of models as ‘heli'$_{cyl}$’ and consider a range of $\alpha \in [3\degree, 87\degree]$. A 3D representation of the toroidal and helical, respectively, field can be found in panels (b) and (c) of Fig. 1. As the filament moves with respect to the environment, the gas mass will affect the magnetic field morphology. The strength of this effect heavily depends on the trajectory of the gas. Moving gas contracting along magnetic field lines does not influence the magnetic field morphology, while a perpendicular contraction may bend the field symmetrically with respect to the $y$-axis. Assuming the field is initially parallel to the $z$-axis in Fig. 1, such a field morphology can be modeled by the following expression:

$$B(\vec{r}_{cyl}) = \frac{B_0(\vec{r}_{cyl}) \left( \text{sgn}(x) 30 x z^2 \exp(-2z^2), 0, 1 \right)^T}{1 + 900 z^2 x^4 \exp(-4z^2)}. \tag{8}$$

As the magnetic field would abruptly switch sign when $x$ goes from negative to positive, the term $\text{sgn}(x)$ ensures the continuity of the field. We refer to this kind of morphology emerging from a contracting filament as model ‘cont’; see also panel (d) in Fig. 1. Contraction of mass is not limited to a mass flow perpendicular to the symmetry axis. As indicated by numerical simulations (Gomez et al. 2018). Ther
could also be contraction along the filament as in the models by Smith et al. (2016). In our model as well as in observations (e.g. Pattle et al. 2017) a collapse may also take place along the filament. In this case the magnetic field would be warped along the predominant trajectory of the mass, as in panel (e) of Fig. 1. We model the gross geometric characteristics of such a field with a radially dependent Gaussian:

$$B(r_{cyl}) = \frac{B_0(r_{cyl}) (1, 8x \exp(-6(x^2 + z^2)), 0)^T}{1 + 16x^2 \exp(-12(x^2 + z^2))}.$$  \hfill (9)$$

Finally, we consider also the scenario, where an already fully formed filament drifts into a magnetic field morphology with initially parallel field lines (e.g. Inoue et al. 2017):

$$\vec{B}(r_{cyl}) = \frac{B_0(r_{cyl}) (1, 0, -5z(2-z)^2 \exp(-8x^2))^T}{1 + 25z^2(2-z)^4 \exp(-16x^2)}.$$  \hfill (10)$$

where the amplitude of the disturbance depends on the $x$-coordinate (see panel (f) in Fig. 1).

As for the magnitude of the magnetic field strength we consider two cases. First, we assume the filament to be magnetized with a constant field strength of $B_0(r_{cyl}) = 100 \ \mu G$. In the second case we apply the familiar scaling-law (Crutcher et al. 1993; Crutcher 1999) of field strength with volume density $n_{\text{gas}}$:

$$B_0(r_{cyl}) \propto n_{\text{gas}}^{0.6}(r_{cyl}).$$  \hfill (11)$$

Here, we re-scale in order to obtain a field strength at $B_0(r_{cyl} = 0) = 100 \ \mu G$ in the center of our filament model.

3 RADIATIVE TRANSFER (RT)

3.1 Molecular abundances and gas temperature

We use the spectral synthesis code CLOUDY$^3$ v17.00 (Ferland et al. 2017) to calculate the total gas temperature $T_g$ and molecular abundances of the HI, OH, CN, and SO along the radial density profile of our filament model. The results are shown in Fig. 3 (see also Table 1). The abundances are calculated under the assumption of steady state. Heating and cooling are assumed to be in local equilibrium, with the temperature and abundance gradient set by the density gradient and the attenuated incident radiation field and

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$^3$ http://www.nublado.org/
Figure 9. The same as Fig. 8 for the model ’cont’.

3.2 Grain alignment and dust heating

For the dust heating and polarization calculations we apply the code RT code POLARIS (Reissl et al. 2016). The implementation of the dust heating follows the Monte-Carlo based method presented in Lucy (1999). This method assumes that the dust grains exist in thermal equilibrium with their environment:

\[
\frac{E_0}{V} \sum_i C_{\text{abs}, \lambda} \frac{l_i}{v} = 4\pi \int C_{\text{abs}, \lambda} B_{\lambda}(T_{\text{dust}}) d\lambda, \tag{12}
\]

where a photon deposits an energy of \(E_0\) per unit time in a cell of volume \(V\) along its path \(l_i\) between two cell walls. Comparing this energy content with the blackbody spectrum \(B_{\lambda}(T_{\text{dust}})\) modified by the cross section of absorption \(C_{\text{abs}, \lambda}\) allows the derivation of the dust temperature \(T_{\text{dust}}\) assuming typical Milky Way conditions.

The usual way to quantify polarized radiation is with the help of the Stokes vector \(S = (I, Q, U, V)^T\). The Stokes parameter \(I\) stands for the total intensity, whereas \(Q\) and \(U\) quantify the linear polarization and \(V\) the circular polarization. POLARIS solves the RT problem self-consistently in all four Stokes parameters simultaneously (Whitney & Wolff 2002; Reissl et al. 2016). The polarization state of observed radiation is then completely defined by the degree of linear polarization,

\[
P_L = \sqrt{\frac{Q^2 + U^2}{I^2}},
\]

the orientation angle,

\[
\chi = \frac{1}{2} \tan^{-1} \left( \frac{U}{Q} \right),
\]

as well as the degree of circular polarization

\[
P_c = \frac{V}{I}.
\]

Note that \(P_L\) is always positive while the \(P_c\) can also have negative values for light with circular polarization rotating counter clockwise (depending on the convention) in direction of the observer.

The local dust polarization within the model varies depending on the local conditions of the model as well as the grain parameters. Hence, another model parameter important for the polarization measurements of filaments is the cosmic ray ionization rate. This provides heating as well as increases the abundance of free electrons. Two 1D calculations are performed, each for a power-law profile with the slope \(\beta\) equal to 1.6 and 2.0, respectively, with initial densities. Milky Way conditions were assumed by adopting Orion nebular metal abundances (Baldwin et al. 1991). Calculations assume a constant Galactic cosmic ionization rate. The calculations were stopped when an equilibrium temperature was reached.
alignment efficiency of the dust grains. In contrast to previously attempts to model dust polarization (e.g. Fiege & Pudritz 2000b), the RT code POLARIS provides the full spectrum of available grain alignment theories.

The physics of grain alignment is still a field of ongoing research (see Andersson et al. 2015, for review). However, the most dominant cause and widely accepted mechanism of dust grain alignment is by means of radiative torques (RAT) (Weingartner & Draine 2003; Lazarian & Hoang 2007). In order for paramagnetic grains to align efficiently with the magnetic field direction they must spin with a sufficiently large angular momentum $J$. Irregularly shaped dust grains can spin up by a directed beam of radiation as well as gas collisions. The later effect leads to an angular momentum $J_{\text{gas}}$ pointing in a random direction. Hence, one criteria for grain alignment is if the spin up process is dominated by RATs. As it is shown in Hoang & Lazarian (2008) a stable alignment can only take place when the rotational angular momentum $J_{\text{rot}}$ induced by RATs is about a factor of $3\times$ larger than the angular momentum $J_{\text{gas}}$ by dust-gas collisions. This necessary condition can be expressed as (Draine & Weingartner 1996, 1997; Weingartner & Draine 2003):

$$\left( \frac{J_{\text{rot}}}{J_{\text{gas}}} \right)^2 \approx \frac{a_{\text{dust}} \rho_{\text{dust}}}{\delta m_{\text{H}}} \times \left( \frac{t_{\text{gas}}}{(t_{\text{gas}} + t_{\text{rot}}) n_{\text{gas}} k_{\text{B}} T_{\text{gas}}} \int Q_{\text{rad}} \gamma_{\lambda} \pi_{\lambda} d\lambda \right)^2.$$  \hspace{1cm} (16)

Here $m_{\text{H}}$ and $k_{\text{B}}$ are the hydrogen mass and Boltzmann’s constant, respectively. The density of the grain material $\rho_{\text{dust}}$, the geometric factor $\delta$ as well as the grain alignment efficiency $Q_{\text{rad}}$ are defined by the choice of the dust grain model as it is defined in Sect. 2.2. Grain rotation is dumped down by gas collision as well as the emission of thermal photons. These effects are taken care by the gas dumping time $t_{\text{gas}}$ as well as radiative dumping time $t_{\text{rot}}$ (we refer to Draine & Weingartner 1996, for exact definitions). The mean energy density $\varepsilon_{\lambda}$ per wavelength as well as the anisotropy factor $\gamma_{\lambda}$ factor are calculated in a Monte-Carlo run with POLARIS assuming typical Milky Way conditions (see Reissl et al. 2016, for details). Hence, the grain radius $a_{\text{dust}}$ represents a lower threshold for effective grain alignment. Consequently, the ratio $(J_{\text{rot}}/J_{\text{gas}})^2$ in Eq. 16 amounts to a lower value in the central regions of the filament model where the density is highest and the radiation field is not capable of penetrating efficiently.

The magnetic field strength also plays a role in determining whether or not grains can become aligned via RATs. Thus, a second criteria for RAT alignment concerning the critical magnetic field strength arises by comparing the gas dumping time with the Larmor precession time scale (see e.g. Hoang & Lazarian 2008; Lazarian & Hoang 2007). However, this criteria is always fulfilled for the particular filament model presented in this work and is thus only mentioned for completeness. The degree of grain alignment per grain size can be quantified with the help of the Rayleigh reduction...

**Figure 10.** The same as Fig. 8 for the model ‘bow’.
factor (RRF) $R(a_{\text{eff}}) \in [0 : 1]$ (see e.g. Greenberg 1968; Lazarian 1996) where $R(a_{\text{eff}}) = 0$ means random alignment and $R(a_{\text{eff}}) = 1$ stands for perfect alignment (in principle, the definition of the RRF allows also for negative values but these are irrelevant considering only RAT alignment).

A stable dust grain alignment can either occur with the direction angular momentum $J$ pointing parallel or anti-parallel to the magnetic field direction. The parallel configuration comes with perfect alignment where as at the anti-parallel one the dust grain precesses with $J$ around $B$ (Roberge & Lazarian 1999; Hoang & Lazarian 2014). This case can be accounted by the factor $R_{||}$. By introducing the ratio $f_p$ of dust grains aligning with the parallel configuration the RRF can be expressed as:

$$R(a_{\text{eff}}) = \begin{cases} f_p + (1 - f_p) R_{||} & \text{if } a_{\text{eff}} > a_{\text{alg}} \\ 0 & \text{otherwise}. \end{cases}$$

(17)

Using canonical values (Hoang & Lazarian 2014; Reissl et al. 2016) it gives $f_p + (1 - f_p) R_{||} \approx 0.72$.

Two aspects of dust polarization measurements can help to deduce the magnetic field morphology. First, any rotating dust grain aligned with the magnetic field direction would appear spherical when observed along a LOS parallel to the magnetic field direction. Meanwhile, an observation perpendicular to the magnetic field lines would result in maximal polarization (see also Fig. 2). For emission in the IR and sub-mm regime, the size-averaged cross section of polarization $\Delta C_{\lambda}$ can be calculated as:

$$\Delta C_{\lambda} \cong \sin^2(\vartheta) \int_{a_{\text{low}}}^{a_{\text{up}}} R(a) n(a) \times (C_{\text{abs},\lambda,\perp}(a) - C_{\text{abs},\lambda,||}(a)) \, da,$$

(18)

where $\vartheta$ is the angle between LOS and magnetic field direction and the cross sections of absorption $C_{\text{abs},\lambda,\perp}(a)$ and $C_{\text{abs},\lambda,||}(a)$ are perpendicular and parallel, respectively, with respect to the minor and major axis of a spheroidal dust grain. Hence, no polarization can take place along the LOS.

Second, due to a differential phase lag for different polarized states, a portion of the linear polarization passing through the material obtains a small degree of circular polarization (for details we refer to Martin 1971; Whitney & Wolff 2002; Reissl et al. 2016). This conversion is most effective in case when the dust grain alignment neither parallel nor perpendicular to the LOS. Consequently, circular dust polarization is an indicator of non-parallel magnetic field lines along the LOS. Formally there can be also a contribution to circular polarization due to dust scattering. However, since the scattering cross sections are minuscule at long wavelengths we ignore this effect in this paper.

3.3 Line of sight (LOS) Zeeman effect

The Zeeman effect provides the means to observe the LOS magnetic field strength (e.g., Crutcher et al. 1993; Crutcher...
Table 1. Characteristic frequency $\nu_0$ and Zeeman shift $\nu_z$ for the different molecules considered in this work.

| Molecule | HI$_{2-1}$ | OH$_{3-1}$ | CN$_{1-2}$ | SO$_{4-3}$ |
|----------|-----------|-----------|-----------|-----------|
| $\nu_0$ [GHz] | 1.420 | 1.665 | 133.171 | 99.30 |
| $\nu_z$ [Hz/$\mu$G] | 2.80 | 3.27 | -0.21 | 1.01 |

(1999). Certain molecular energy levels can split into sub-levels in the presence of a magnetic field. This gives rise to counter clockwise ($I_{ccw}$) and clockwise ($I_{cw}$) circularly polarized radiation, respectively. Hence, the Stokes parameters of intensity and circular polarization are determined by

$I = I_{ccw} + I_{cw}$

and

$V = I_{cw} - I_{ccw} = \frac{dl}{d\nu}\Delta \nu_z \cos(\theta)$.  

Here, $\theta$ is defined as the angle between the LOS and the magnetic field direction. The frequency shift caused by the Zeeman splitting is defined as

$\Delta \nu_z = \frac{B\mu_B}{h} \left(g' M' - g'' M''\right)$,  

where $\mu_B$ is the Bohr magneton, $h$ is the Planck constant, and $M$ and $g$ are the magnetic quantum number and Lande$\acute{e}$ factors of the lower sub-level (superscript $'$) and upper sub-level (superscript $''$), respectively (see also Tab. 1).

We perform line RT simulations with the POLARIS code (see Brauer et al. 2017, for details). POLARIS can solve the line RT problem considering the level populations of a certain molecule including Zeeman splitting based on the physical parameter taken from Leiden Atomic and Molecular Database LAMDA$^4$ (Schoeier et al. 2006). For calculating the level populations we consider the conditions of local thermodynamic equilibrium (LTE), or alternately use the free-escape probability (FEP) implemented in POLARIS. The later assumes that the radiation interacts with the molecule only once and escapes then freely from the cube of the model. Both LTE as well as FEP deliver almost identical results for our filament model. Hence, all the results presented here are calculated with the computationally lighter LTE condition. The characteristic transition frequency $\nu_0$ between molecular sub-levels is broadened by Doppler shifting. Here we take total velocity to be $v = v_{rad} + v_{rot}$ (see Sect. 2.1).

Additionally, POLARIS takes the effects resulting from natural and collisional broadening as well as magneto-optical effects, as presented in Larsson et al. (2014), into account, while performing line RT with Zeeman splitting.

Finally, the remaining parameters are the magnetic field strength $B$ and the cos($\theta$). These quantities are indirectly determined by least square fitting the Stokes $V$ parameter in Eq. 20 resulting from the POLARIS line RT simulations to $dI/d\nu$. In this work we are dealing with idealized and synthetic observational conditions and the LOS magnetic field strength

$B_{||} = B \cos(\theta)$

can be inferred from synthetic Zeeman observations by a single parameter fit (instrumental effects may require additional parameters). Note that LOS and $B$ can be either parallel or anti-parallel because of the cos($\theta$). Hence, for Zeeman measurements the magnitude of $B_{||}$ as well as its sign can provide valuable information about the observed projected magnetic field morphology. The necessary quantities for the fitting process are listed in Tab. 1.

4 http://home.strw.leidenuniv.nl/~moldata/

4 DISCUSSION

4.1 Dust polarization measurements

We perform RT dust polarization simulations along the observer plane (see black dashed lines in panel (a) of Fig. 1) for the different magnetic field morphologies in order to investigate the emerging polarization pattern as a function of wavelength and filament inclination. Here we consider the Herschel (Pilbratt et al. 2010) bands $\lambda \in [160 \mu m, 250 \mu m, 350 \mu m, 500 \mu m]$, similar to the high frequency bands of ALMA, and rotate the model by an inclination of $i \in [0^\circ, 90^\circ]$ in steps of 15° around the x-axis (see Fig. 1), where $i = 0^\circ$ is a LOS perpendicular to the symmetry axis of the filament.

The resulting degrees of polarization and the orientation of polarization vectors are rather similar for the applied regime of wavelengths. The polarization appears also to be only mildly affected by the power law index $\beta$ of the density profile and the radial dependence of the magnetic field strength. Hence, we focus in our discussion on a wavelength of $\lambda = 500 \mu m$, a slope of $\beta = 2.0$ and the radially dependent magnetic field case (see Eqn. 11).

In Fig. 4 we present plots of the orientation and degree of linear polarization $P_1$ as well as the degree of circular polarization $P_c$. In the upper row we show the results for the model ’toro’. For an inclination of $i = 0^\circ$ the toroidal field exhibits a pattern of polarization vectors that are parallel to the long-axis of the filament. Note that this pattern is in thermal emission. Hence, the magnetic field can be inferred along the perpendicular direction. This orientation pattern would also be characteristic for magnetic field lines with an orientation parallel to the x-axis. However, the degree of linear polarization is different. A purely parallel field would be rather constant with decreasing radius $r$ with a minor drop close to $r = 0$ pc. This drop is a result of an inefficient grain alignment close to the symmetry axis of the filament (see Sect. 3.2). In contrast to a parallel field a toroidal field has components perpendicular to the LOS (the same as scenario (A) in Fig. 2). Consequently, the degree of linear polarization peaks toward the center. Here, the magnetic field morphology is the dominant parameter compared to grain alignment. Since the toroidal morphology has no crossing field lines along the LOS we can observe no circular polarization signal at zero inclination. For a toroidal field the overall pattern of polarization orientation does not change between $i = 0^\circ$ – $30^\circ$. At this characteristic value the magnetic field lines start to cross (see scenario (B) in Fig. 2). As a consequence, linear polarization cancels out at a certain radius and circular polarization starts to emerge from the filament. For the purely toroidal field, the degree of circular polarization increases with increasing inclination angles. Both the linear as well as the circular polarization patterns
are symmetric with respect to the symmetry axis of the filament. The cancellation points in the polarization degree coincide with the location where the polarization changes its direction by 90°, which we term the “flipping point” of the orientation vectors. A flipping point is a characteristic feature of the projected field morphology and not a consequence of grain alignment and thus we suggest that it may be a very useful diagnostic of the underlying field morphology.

We present the dust polarization results of the model ‘cont’ in the second top row of Fig. 4. The amount of \( P_i \) at \( r = 0 \) pc is not the absolute maximum of the plot but is slightly reduced by the inefficient grain alignment close to the center of the filament. In comparison with the toroidal field this morphology has no crossing field lines along the LOS and, hence, no circular polarization for zero inclination and the polarization pattern are rather similar. In contrast to model ‘toro’ the model ‘cont’ has its field lines parallel to the LOS for \( i = 0° \) and \( r = 0 \) pc. As a result of this, there is no measurable degree of linear polarization close to the symmetry axis of the filament. As the inclination increases, the central field lines would go from parallel to perpendicular with respect of the direction of the LOS. Hence, the amount of \( P_i \) increases with increasing inclination. However, the central magnetic field lines do not cross independent of inclination. Thus, the degree of circular polarization \( P_c \) remains at a minimum at \( r = 0 \) pc. In contrast to toroidal and helical fields the distance between flipping points increases with increasing inclination.

The next row in Fig. 4 shows pattern and degrees of polarization for the model ‘bow’. In contrast to all models previously discussed, this model has no flipping points at all. Indeed, the field lines do cross along several LOS with decreasing observer plane while at the center all lines are parallel again. Hence, two characteristic lobes are present in the degree of linear polarization \( P_l \). However, adjacent field lines seem never to be parallel along the LOS. Hence, \( P_l \) can never go to zero and the polarization vectors do not flip. Furthermore, the overall polarization pattern changes only slightly with increasing inclination. The small drop in circular polarization \( P_c \) can be traced back to the diminished grain alignment in the center of the filament.

Finally, the bottom panels of Fig. 4 show the polarization behavior the model ‘flow’ for the RT simulations. While models ‘bow’ and ‘flow’ are intended to model completely different scenarios for how magnetic field morphologies may be warped by a moving filament, their polarization patterns are very similar. Yet again, model ‘flow’ shows no signatures of flipping points. Whereas the pattern of polarization vectors goes from a vertical polarization to almost diagonal for ‘flow’ and an increasing inclination this trend is reversed for ‘bow’. For model ‘flow’ the degree of \( P_l \) shows also two characteristic minimums comparable to those of the model ‘bow’. However, for model ‘flow’ these minimums do not arise from crossing field lines but are a result of the vertical components of the warped field at a radius of about \( r = 5 \) pc. Circular polarization of model ‘flow’ covers a larger range concerning minimum and maximum values while the range and slope are similar to those of model ‘bow’. These results indicate that models ‘flow’ and ‘bow’ would be hardly to distinguishable using dust polarization measurements alone.

Actual dust polarization measurements presented in Pattle et al. (2017) of the OMC 1 region in the Orion A filament appear to be similar to that shown in the bottom two rows of Fig. 4. Here, Pattle et al. (2017) interpret their data as consistent with a scenario where a cylindrically symmetric field becomes distorted by means of gravitational fragmentation. However, such measurements (in the absence of Zeeman information) do potentially allow for an alternative explanation because of the similarities between the models ‘flow’ and ‘bow’. As demonstrated in this paper, the polarization a filament moving toward the observer, in the process sweeping up the homogenous magnetic field, causes the same dust polarization signature as the scenario of a presented Pattle et al. (2017). Again, a complementary observational mission considering additional Zeeman measurements may help to to infer the actual field morphology in the OMC 1 region. In summary, Zeeman observations will likely prove essential for differentiating between models that generically appear similar in linear polarization alone.

Additionally, circular dust polarization can help reveal the magnetic field morphologies embedded in the filaments by their characteristic profiles. This was already demonstrated in Reissl et al. (2014) for globules. However, it needs to be emphasized, as above, that an amount \( P_c \) far below one percent will be challenging to detect circular dust polarization with real observations in the near future.

### 4.2 Influence of the pitch angle on dust polarization

The polarization pattern emerging from helical fields are highly dependent on the pitch angle \( \alpha \). In Fig. 5 we show this dependency for different pitch angles and inclinations. The figure is structured in the same manner as Fig. 4. However, different rows show different pitch angles for the helical configuration. With increasing \( \alpha \) the helical field goes from toroidal (top rows) to poloidal (bottom row). Hence the flipping points wander towards the symmetry axis of the filament and the polarization pattern becomes almost parallel for low inclination and high pitch angles. We note that the degree of linear polarization is highest for high inclinations and low pitch angles while this is the opposite for a high pitch angle.

Since this kind of field has crossing field lines along the LOS for the entire range of inclination angles the polarization pattern starts again with a constant pattern of orientation vectors at zero inclination. However, compared to the toroidal field the vectors are already flipped as a consequence of a pitch angle of \( \alpha = 45° \). The most important feature of helical fields is their asymmetry with respect to the symmetry axis of the filament: compare panels b. and c. in Fig. 1. Hence, the number of crossing field lines is no longer evenly distributed along all directions of the observer plane. This asymmetry results in flipping points only appearing for positive values of \( r \). Consequently, the orientation of linear polarization flips only for positive values of \( r \) where as the polarization pattern remains constant for negative \( r \). The toroidal field case the circular polarization changes sign at \( r = 0 \) pc where as the helical field has only positive values of \( P_c \) for \( r < 0 \) pc, where as for \( r > 0 \) pc shows both negative as well as positive values.
4.3 Characteristic distances of flipping points

We note also a tight correlation between the radial distance $\Delta r$ of flipping points and the inclination angle $i$. This correlation is characteristic of the different applied magnetic field morphologies, as noted above. In Fig. 6, we show the radial distances of the models ‘toro’ and ‘cont’. For the model ‘toro’ the distance between the flipping points becomes narrower, whereas for model ‘cont’ we see the opposite trend. For the model ‘toro’ the flipping points start to emerge at $i = 30^\circ$ while the model ‘cont’ has flipping points even at $i = 0^\circ$ up to $i \approx 80^\circ$. The general trends are almost independent of wavelength $\lambda$ and the slope parameter $\beta$ for both models.

The same for the set of models ‘heli’ presented in Fig. 7. Here, we show the behavior of flipping point for a helical field for different pitch angles and inclinations. The distance of flipping points increases for model ‘heli$\,_{55}$ with increasing inclination $i$ and reaches a plateau for $i \in [30^\circ, 60^\circ]$ and reaches $\Delta r = 0$ pc again at $i = 90^\circ$ again. Observed under an inclination of $i = 0^\circ$ the flipping points begin to emerge over a range of pitch angles $\alpha \in [25^\circ, 45^\circ]$ where the radial distance goes from the maximum extent of the filament toward $\Delta r = 0$ pc.

We speculate that the trend between the distance of $\Delta r$ flipping points might help determine the inclination of a filament provided that the underlying magnetic field morphology can be well enough constrained in the first place.

4.4 Zeeman observations

The results presented here are extracted from RT simulations with the ZRAD module of POLARIS for the different magnetic field models that we consider (see Fig. 1). We then fit the resulting Stokes parameter as described in Sect. 3.3 to create synthetic Zeeman observations. We consider the characteristic transitions listed in Tab. 1 for an inclination of $i = 0^\circ$ as well as the different cases of a constant magnetic field strength of $B_0(r_{cyl}) = 100 \mu$G and a radial magnetic field proportional to the volume density, as described in Sect. 2.3. Furthermore, we compare results of a synthesized molecular abundance (see Sect. 3.1) and a constant abundance of $n/\rho_{\text{gas}} = 10^{-6}$. Fig. 8 shows the derived LOS magnetic field strengths $B_{||}$ for the toroidal model ‘toro’. Because $B_{||} \propto \cos(\theta)$, the magnitude of $B_{||}$ drops towards the center even for the case of a constant field strength (compare also to the sketch in Fig. 2, right panel). However, some lines show an exceptional behavior with an increase of $B_{||}$ toward the center. If the magnetic field strength becomes too high in comparison to the line width, the analysis method introduced in Sect. 3.3 no longer applies (this case is extensively modeled and discussed in Brauer et al. 2017). The strongest effect is for OH and HI the most considering the low gas temperature in the center of the filament (see Fig. 3). Hence, the synthetic Zeeman measurements of $B_{||}$ are less reliable at the center of our filament model.

We note that this behavior is also highly dependent on the magnitude of the of turbulent $v_{\text{turb}}$ component of the gas velocity. A higher $v_{\text{turb}}$ would cause a better tracing of the magnetic field strength. For a $v_{\text{turb}} \gtrsim 1000$ km/s all the lines would show the decrease in $B_{||}$ close to the center that is characteristic of a toroidal magnetic field morphology (see e.g. Brauer et al. 2017). Therefore, the strong increase of a toroidal field close to the center would be better traced and almost no drop would be seen.

However, such a high values would be in direct contradiction with observations (e.g. García-Díaz & Henney 2007; Arthur et al. 2016). Concerning the slopes, the results of the model ‘heli$\,_{55}$ are almost identical with the profiles shown in Fig. 8. However, the magnitudes are about a factor of 1.2 to 2 lower because of the poloidal component of the field in ‘heli$\,_{55}$ is no longer detectable.

The line profiles shown in Fig. 9 result from the model ‘cont’. For this particular morphology the field lines are parallel to the LOS at the center. Hence, we observe an increase in the LOS magnetic field component $B_{||}$ with the maximum at $r = 0$ pc for all considered parameters. Here, all Zeeman profiles presented in Fig. 9 follow the behavior expected for model ‘cont’.

In contrast to the dust polarization measurements the models ‘bow’ and ‘flow’ show a distinct behavior in Zeeman observations. Because the magnetic field follows the gas flow in model ‘bow’ the magnetic field is mostly warped in a direction perpendicular to the LOS (compare panel e in Fig. 1). Hence, the derived $B_{||}$ is up to 15 order of magnitudes lower the the actual magnetic field strength as shown in Fig. 10. This renders it impossible to constrain the morphology by means of Zeeman measurements. Model ‘flow’ has field lines perpendicular to the LOS at the outer edges of the model as well as in the center. Thus, the derived magnetic field strength $B_{||}$ rises toward the center, with a drop near the center itself. This characteristic shape and the magnitude makes the model ‘flow’ clearly distinct to the model ‘bow’.

As shown in Figs. 8-11, all simulated Zeeman observations share the common feature that underestimate the actual magnetic field strengths in the model by significant and sometimes very large factors. This decrement is caused by the intensity averaging along a cord intersecting a filament with a radially declining volume density profile. This result has important implications for the observed Zeeman-derived field strengths and will be investigated in detail in an upcoming paper.

4.5 Chandrasekhar-Fermi method

In addition to the methods already discussed in this work, the Chandrasekhar-Fermi (CF, Chandrasekhar & Fermi (1953)) method does allow to determine the magnetic field component $B_{||}$ perpendicular to the LOS, by linking the dispersion in the velocities to the dispersion in the polarization orientations (e.g. Pillai et al. 2016). CF assumes that the magnetic field is frozen into the matter following the magnetic and turbulent energy densities. If these assumptions hold, this method would provide the means to complement Zeeman measurements to estimate the total magnetic field strength. In this work both quantities are modeled with values close to what we know from observations. However, in our simple initial approach we do not have any dispersion in polarization angles arising from turbulence and CF breaks down within framework of our model.

More generally, the overarching issue here is the assumption of an B-fields coupling to the gas. Under which conditions the field may essentially be following the turbu-
lent flow, such that the dispersion in the polarization angles can be interpreted in a statistical sense as a field strength (Crutcher 2012; Planck Collaboration et al. 2016b) remains an important but highly complex open question. Hence, providing a physically well motivated model for predicting the \( B_\parallel \) by applying CF to synthetic dust polarization measurements and line RT is well beyond the scope of the current study.

5 SUMMARY AND CONCLUSIONS

In this paper, we present a simple model of a filament considering several scenarios for warped 3D magnetic fields. We performed RT simulations in order to identify the characteristic observables that may help to distinguish between different field morphologies. Here, we used sophisticated state-of-the-art RT simulations within the framework of POLARIS (Reissl et al. 2016; Brauer et al. 2017) in order to derive synthetic dust polarization pattern and Zeeman LOS magnetic field measurements for the magnetic field configurations presented in Fig. 1. Our results are summarized as follows:

- We find that linear dust polarization is insufficient to constrain the underlying magnetic field morphology in filaments. Different morphologies are degenerate and result in similar dust polarization patterns (see the lower two rows in Fig. 4).
- As in Reissl et al. (2014) we show that circular dust polarization \( P_c \) in filaments provides a useful means with which to constrain the 3D magnetic field morphology, complementing linear polarization in a substantive way. However, some field morphologies remain ambiguous. Neither linear nor circular dust polarization provide direct field strengths; nevertheless, despite low fractions, observing dust circular polarization would provide important meaningful field information.
- We find a low degree of circular dust polarization \( P_c \). This result requires further investigation to determine whether the expected low levels of \( P_c \) would be detectable by upcoming observing machines. A more extensive investigating the effects of dust models, mass, temperatures may reveal the necessary conditions for detecting the circular dust polarization signal.
- The magnetic field in filaments leaves an imprint that is detectable in the Zeeman line splitting through the line-of-sight field direction and strength. The low temperatures and velocities make Zeeman measurements unreliable in the very center of filaments (see Brauer et al., 2017, for details). Nevertheless, the Zeeman parameters provide essential constraints to interpret, together with the dust polarization measurements, the 3D field configuration, such as providing direct field directions on either side of the filament.
- Within the parameter space of our filament models we show that the projected LOS magnetic field observed by Zeeman measurements always underestimate the actual field strengths within the filament by large factors (\( \times 2 \) to more than \( \times 10 \)). The implications of this finding will be investigated in an upcoming publication.
- Finally, we note that both dust polarization and Zeeman observations together are essential for constraining the 3D field morphology. We suggest that an observing strategy consisting of cuts perpendicular to main filament axis will provide optimal diagnostic power necessary to constrain 3D magnetic field morphologies.

We emphasize that the results presented here are highly idealized synthetic observations that capture the principal observational signatures of selected magnetic field morphologies without regarding for telescope or instrumental effects. Thus, careful consideration must be taken when comparing to real telescope observations. For example, in the work presented here we have omitted various effects such as sensitivity, noise, and spatial filtering, all of which are likely to play an important role in the interpretation of e.g. ALMA measurements. Moreover, a meaningful interpretation of any polarization measurements must account for noise, as opposed to only consider the geometric projections of “pseudovectors”. Thus we recommend careful interpretation the polarization orientation information obtained from real observations for two related if distinct reasons. First, real observational effects may mimic differing field geometries, and second, the presence of 3D curved field geometries leaves an imprint on the observations which cannot be accurately interpreted under the assumption of a basically 2D field configuration. In a future work we will address the observational issues mentioned above with the goal of generating synthetic observations combined with simulated instrumental effects.

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