Magnetic field structure of OMC-3 in the far infrared revealed by SOFIA/HAWC+

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ABSTRACT

We report the SOFIA/HAWC+ band D (154 \( \mu \)m) and E (214 \( \mu \)m) polarimetric observations of the filamentary structure OMC-3 that is part of the Orion molecular cloud. The polarization pattern is uniform for both bands and parallel to the filament structure. The polarization degree decreases toward regions with high intensity for both bands, revealing a so called "polarization hole." We identified an optical depth effect in which polarized emission and extinction act as counteracting mechanisms as a potential contributor to this phenomenon. Assuming that the detected polarization is caused by the emission of magnetically aligned non-spherical dust grains, the inferred magnetic field is uniform and oriented perpendicular to the filament. The magnetic field strength derived from the polarization patterns at 154 \( \mu \)m and 214 \( \mu \)m amounts to 202 \( \mu \)G and 261 \( \mu \)G, respectively. The derived magnetic field direction is consistent with that derived from previous polarimetric observations in the far infrared and submillimeter (submm) wavelength range. Investigating the far-infrared polarization spectrum derived from the SOFIA/HAWC+ observations, we do not find a clear correlation between the polarization spectrum and cloud properties, namely, the column density, \( N(H_2) \), and temperature, \( T \).

Key words. magnetic fields – polarization – Techniques: polarimetric – ISM: magnetic fields – ISM: individual object: OMC-3

1. Introduction

Magnetic fields in astrophysical objects are ubiquitous and can be found on both small and large scales. However, the role of magnetic fields in various physical processes, in particular, star formation, is a matter of ongoing debate. For instance, magnetic fields are considered as a mechanism which slows down the contraction of star-forming regions and filaments, thus, providing a possible explanation for the low star formation rates that have been observed (Van Loo et al. 2015; Federrath 2015). Polarimetric observations have revealed a highly ordered large-scale magnetic field structure and strength in star-forming environments.

It is assumed that radiative torque (RAT) alignment is the underlying process for aligning the dust grains. Here, elongated dust grains spin up and align with their longer axis perpendicular to the magnetic field lines due to the Barnett effect (Barnett 1915; Lazarian 2007; Lazarian & Hoang 2007; Hoang & Lazarian 2009) in the presence of an anisotropic radiation field (e.g., a central star embedded in a circumstellar envelope).

A broad range of attempts has been undertaken to detect this polarized radiation, such as with JCMT/SCUBA-2 (Holland et al. 2013), the Planck satellite (Planck Collaboration et al. 2011), and ALMA. In recent years, HAWC+ (Harper et al. 2018) aboard the Stratospheric Observatory for Infrared Astronomy (SOFIA) opened the far-infrared view for polarimetry. Using SOFIA/HAWC+, galaxies (Jones et al. 2020; Lopez-Rodriguez et al. 2020), Bok globules (Zielinski et al. 2021), prestellar cores (Redaelli et al. 2019) and filaments (Chuss et al. 2019) have been observed.

In the context of high-mass star formation, highly supercritical filaments are of particular interest. Using the Herschel Space Observatory (Pilbratt et al. 2010), filamentary structures in the interstellar medium have been detected (e.g., André et al. 2010; Schisano et al. 2020). These observational results agree well with the predictions from numerical studies, which are showing that the ISM should be highly filamentary on all scales and star formation is linked to self-gravitating filaments (see André et al. 2014, for a review of this topic). Understanding the physical properties of filaments is therefore crucial for understanding star formation in depth on galactic scales.

Since the Orion molecular cloud complex is the closest region that is undergoing massive star formation, it has been studied intensively. We present polarimetric observations of OMC-3, a star-forming region at a distance of 388 pc (Kounkel et al. 2017), which is part of the integral shape filament of the Orion molecular cloud. Several prestellar and protostellar sources have been identified in OMC-3 (Chini et al. 1997). The protostellar sources in this region include Class 0 and Class I protostars (e.g., Chini et al. 1997; Nielbock et al. 2003). MMS6 is the brightest source in OMC-3 with at least a factor of five larger flux density at (sub)millimeter wavelengths, as compared to all the other OMC-2/3 sources (Matthews et al. 2005; Takahashi et al. 2009). MMS6 has a bolometric luminosity of \( L_{\text{bol}} < 6 \times 10^3 \) and a core mass of \( M_{\text{core}} = 30 M_\odot \) (Chini et al. 1997). Furthermore, multiple radio jets, molecular outflows, and shock-excited H\(_2\) emission have been detected (Yu et al. 1997; Reipurth et al. 1999; Asó et al. 2000; Stanke et al. 2002; Matthews et al. 2005). In particular, OMC-3 is a well-studied region with polarimetric observations ranging from the far infrared to submillimeter (submm) and millimeter (mm) wavelengths (e.g., Matthews et al. 2001; Houde et al. 2004; Takahashi et al. 2019; Liu 2021). SCUBA and Hertz polarimetric observations have revealed a highly ordered large-
scale magnetic field for OMC-3, perpendicular to the filament. However, Takahashi et al. (2019) and Liu (2021) showed that the small-scale magnetic field has more complex structures using JVLA and ALMA observations. High-resolution polarimetric observations in the far-infrared enable further insights and restrictions of the properties of the magnetic field and the dust by, for instance, studying the polarization spectrum. The polarization spectrum, namely, the polarization degree as a function of wavelength, was first measured in the far-infrared by Hildebrand et al. (1999) using the Kuiper Airborne Observatory. Since then, a great deal of work has been carried out on the basis of observations (e.g., Vaillancourt et al. 2008; Vaillancourt & Matthews 2012; Gandilo et al. 2016) and theoretical frameworks (e.g., Bethell et al. 2007; Draine & Frazier 2009; Guillot et al. 2018) in an effort to understand and interpret this quantity. Using the SOFIA/HAWC+ polarization, it is nowadays possible to study the polarization spectrum more precisely, that is, with higher angular resolution and sensitivity (e.g., Santos et al. 2019; Chuss et al. 2019). We report the polarimetric observations of OMC-3 at 154 µm and 214 µm obtained with SOFIA/HAWC+, which provide further insights into the magnetic field properties and the far-infrared polarization spectrum of this region of interest.

This paper is organized as follows. In Section 2, we describe the data acquisition and reduction and the selection criteria we apply to constrain the data. In Section 3, we present the polarization maps of OMC-3 and the corresponding analysis. We derive the magnetic field structure and strength of OMC-3 in Sect. 3.2. The relation between the polarization degree and the cloud properties is discussed in Sect. 3.3. Additionally, in Section 4, we provide a short discussion of our findings of the magnetic field structure in the context of complimentary polarimetric observations of this source. Finally, we summarize our results in Section 5.

2. Observations

Data acquisition

SOFIA/HAWC+ band D and E observations of OMC-3 were carried out on the 1st of October 2019 as part of the SOFIA Cycle 7 (Proposal 07_0026). Bands D and E provide an angular resolution of 13.6′ and 18.2′ full width at half maximum (FWHM) at the 154 µm and 214 µm center wavelength, respectively. The detector format consists of two 64 x 40 arrays, each comprising two 32 x 40 sub-arrays (Harper et al. 2018). The observations were performed using the chop-nod procedure with a chopping frequency of 10.2 Hz.

The raw data were processed by the HAWC+ instrument team using the data reduction pipeline version 2.3.0. This pipeline consists of different data processing steps including corrections for dead pixels as well as the intrinsic polarization of the instrument and telescope (for a brief description of all steps, see for instance Santos et al. 2019), resulting in “Level 4” (science-quality) data. These include FITS images of the total intensity (Stokes I), polarization degree p, polarization angle θ, Stokes Q and Stokes U, and all related uncertainties. The polarization degree p is calculated via

\[ p = \frac{\sqrt{Q^2 + U^2}}{I} \quad (1) \]

Furthermore, to increase the reliability of our findings, we apply two additional criteria for the data that will be considered in the subsequent analysis:

\[ \frac{I}{\sigma_I} > 100, \quad (2) \]

\[ \frac{\sigma_p}{\sigma_I} > 3, \quad (3) \]

where \( \sigma_I \) and \( \sigma_p \) are the standard deviations of I and p, respectively. In total, we obtained 1299 and 1710 Nyquist-sampled detections at 154 µm and 214 µm, respectively, which meet criteria (2) and (3).

3. Results

3.1. Polarization map of OMC-3

The SOFIA/HAWC+ bands D and E have different fields-of-view, namely, 3.7′ x 4.6′, and 4.2′ x 6.2′ for bands D and E, respectively (Harper et al. 2018). Therefore, we focus on a region with valid polarization data for both bands, that is, polarization data meeting criteria (2) and (3). Figure 1 shows the resulting band D (154 µm, left) and E (214 µm, right) polarization maps of OMC-3, overlaid on the corresponding intensity maps. The complete polarization maps for both wavelengths are shown in Fig. A.1.

Figure 2 shows the distribution of the polarization angles \( \theta \) of OMC-3 for SOFIA/HAWC+ 154 µm (top) and 214 µm (bottom). We mostly find polarization angles ranging from -50° to 10° with clear predominance around -30° for both wavelengths.

In Fig. 3, the distribution of the polarization degree, p, is shown. For both wavelengths the degree of polarization varies between 0.5 % and ~15 %. The polarization degree is in general higher at 154 µm (\( \overline{p}_{154\mu m} = 4.8 \% \pm 2.7 \% \)) than at 214 µm (\( \overline{p}_{214\mu m} = 3.8 \% \pm 2.0 \% \)).

A higher degree of polarization at a shorter wavelength is not expected, but can be explained by the fact that many polarization vectors at 154 µm in regions of higher intensity (lower degree of polarization) do not meet conditions (2) and (3). As a result, most of the polarization vectors are in low-intensity (higher degree of polarization) regions. If we only consider regions of higher intensity (e.g., \( I > 0.2 I_{\text{max}} \)), then the degree of polarization is smaller at 154 µm than at 214 µm (\( \overline{p}_{154\mu m, I>0.2I_{\text{max}}} = 2.3 \% \pm 1.0 \% \), \( \overline{p}_{214\mu m, I>0.2I_{\text{max}}} = 2.5 \% \pm 1.0 \% \)).

3.2. Magnetic field structure and strength

Assuming that the detected polarization is caused by the emission of magnetically aligned non-spherical dust grains, we can rotate the polarization angles by 90° to obtain the projection of the magnetic field direction integrated along the line-of-sight (henceforth, the magnetic field direction). The magnetic field of OMC-3 is visualized using the line-integral-convolution technique (LIC; Cabral & Leedom 1993, see Fig. 4). The intensity is displayed and color-coded, while the LIC textures represent the inferred magnetic field direction. For both wavelengths, the magnetic field direction is oriented perpendicular to the filament structure. This finding is similar to existing polarimetric observations of OMC-3 on similar scales (see Fig. 11, Matthews et al. 2001; Houde et al. 2004).

Referring to the Chandrasekhar-Fermi method (Chandrasekhar & Fermi 1953), we calculate the magnetic field strength of OMC-3 following Patte et al. (2017). Here we are meant to assume that the underlying magnetic field is frozen.
in the cloud material. The plane-of-sky magnetic field strength ($B_{\text{pos}}$) can be calculated according to Crutcher et al. (2004):

$$B_{\text{pos}} = Q \sqrt{4/\pi} \rho \frac{\sigma_r}{\sigma_\theta} \approx 9.3 \sqrt{n(H_2)} \frac{\Delta v}{\sigma_\theta} \mu G,$$

where $\sigma_r$ represents the velocity dispersion, $\sigma_\theta$ the dispersion of the polarization angles, $\rho$ the gas density, $\Delta v$ the velocity dispersion in km s$^{-1}$, $n(H_2)$ the number density of molecular hydrogen,

and $Q = 0.5$ (Crutcher et al. 2004) is a correction factor to account for variation of the field strength on scales smaller than the beam size. As the Chandrasekhar-Fermi method does not constrain the line-of-sight component of the magnetic field strength, the total magnetic field strength amounts to:

$$B = \frac{4}{\pi} B_{\text{pos}}.$$

Fig. 1. SOFIA/HAWC+ band D (154 $\mu$m, left) and E (214 $\mu$m, right) polarization maps of OMC-3. The total intensity is shown with overlaid polarization vectors in blue. The length of the vectors is proportional to the polarization degree and the direction gives the orientation of the linear polarization. The isocontour lines mark 20, 40, 60, and 80% of the maximum intensity. According to criteria (2) and (3), only vectors with $I > 100 \sigma_I$ and $p > 3 \sigma_p$ ought to be considered (see Sect. 2). The beam sizes of 13.6$''$ for 154 $\mu$m and 18.2$''$ for 214 $\mu$m (defined by the FWHM) are indicated in the lower right corners of their corresponding plots.

Fig. 2. Histograms showing the distribution of polarization angles of band D (154 $\mu$m, top) and band E (214 $\mu$m, bottom), respectively. The dashed lines represent the mean polarization angle $\bar{\theta}_D = -32.6^\circ$ and $\bar{\theta}_E = -24.1^\circ$ for 154 $\mu$m, and 214 $\mu$m, respectively. The solid lines represent the corresponding 1$\sigma$ levels, 14.5$^\circ$, and 20.4$^\circ$, respectively.

Fig. 3. Histograms showing the distribution of polarization degrees of band D (154 $\mu$m, top) and band E (214 $\mu$m, bottom), respectively. The dashed lines represent the mean polarization degree $\bar{p}_D = 4.8\%$ and $\bar{p}_E = 3.8\%$ for 154 $\mu$m, and 214 $\mu$m, respectively. The solid lines represent the corresponding 1$\sigma$ levels, 2.7$\%$, and 2.0$\%$, respectively.
For the subsequent analysis, we considered a rectangular area of OMC-3, centered on the point of maximum column density (see Sect. 3.3): R.A. 5h35m20.5s, Dec.-5°00’49’’. The selected area has an angular width of 2’13.2’’ and angular height of 1’36.2’’, corresponding to 0.26 pc and 0.18 pc, respectively, at a distance of 388 pc (Kounkel et al. 2017).

3.2.1. Volume density distribution of OMC-3

To calculate the magnetic field strength of OMC-3, we determine the volume density distribution, the velocity dispersion, and the dispersion of polarization angles.

In Sect. 3.3, we determine the column density across OMC-3 using a single temperature-modified blackbody fit. By using this fitting technique, which includes, among other things, the optical depth and the Planck function, the column density, the temperature, and the dust emissivity index can be derived. To calculate the volume density of OMC-3, we follow Pattle et al. (2017). For the subsequent analysis, we considered a rectangular area of OMC-3, centered on the point of maximum column density (see Table 2 in Aso et al. (2000). Here, several sources, namely AC2, AC3, AC4, are identified which are located within our considered area. The mean velocity dispersion amounts to $\sigma_v = 0.983 \pm 0.005$ km s$^{-1}$.

3.2.2. Velocity dispersion in OMC-3

Aso et al. (2000) observed the OMC-2/3 region in the $^{13}$CO, HCO$^+$ (1-0), and CO (1-0) lines using the Nobeyama 45 m radio telescope. We determined the velocity dispersion of the gas in OMC-3 using the H$^{13}$CO$^+$ observations, as shown in Table 2 in Aso et al. (2000). Here, several sources, namely AC2, AC3, AC4, are identified which are located within our considered area. The mean velocity dispersion amounts to $\sigma_v = 0.983 \pm 0.005$ km s$^{-1}$.

3.2.3. Dispersion of polarization angles

We calculated the standard deviation of the mean polarization angles at 154 $\mu$m and 214 $\mu$m inside our considered area using the 95% confidence interval. We get $\sigma_{\delta, 154} = 11.24^{+0.87}_{-0.75}$ deg and $\sigma_{\delta, 214} = 8.68^{+0.83}_{-0.70}$ deg. In Table 1, we provide an overview of the parameters in relation to the calculation of the magnetic field strength of OMC-3. Using these values, the corresponding plane-of-sky magnetic field strength amounts to 159 $\mu$G and 205 $\mu$G, derived from the 154 $\mu$m and 214 $\mu$m measurements, respectively. The total magnetic field strength amounts to 202 $\mu$G (154 $\mu$m) and 261 $\mu$G (214 $\mu$m). The calculated magnetic field strength values for OMC-3 are lower than the values derived for OMC-1 (300–1000 $\mu$G, Houde et al. 2009; Chuss et al. 2019). The difference can be traced back to the fact that the velocity dispersion for OMC-1 is higher (3.12 km s$^{-1}$, Pattle et al. 2017). Our derived magnetic field strengths are similar to 190 $\mu$G, reported by Poidevin et al. (2010) using 850 $\mu$m SCUBA data for OMC-3 MMS1-7.

Based on the derived magnetic field strength, we calculate the mass-to-flux ratio $\lambda$. We follow Crutcher et al. (2004) to obtain:

$$\lambda = \frac{(M/\Phi)_\text{observed}}{(M/\Phi)_\text{crit}} = 7.6 \cdot 10^{-21} \frac{N(H_2)}{B} \cdot \frac{\mu G}{\text{cm}^2}.$$ (7)

Here, $N(H_2)$ describes the column density and $B$ the magnetic field strength. Using the derived values above, we obtain $\lambda_{154\mu m} = 0.64^{+0.10}_{-0.22}$ and $\lambda_{214\mu m} = 0.49^{+0.07}_{-0.15}$, in particular, both measurements indicate that the filament is subcritical, similarly to OMC-1, where Pattle et al. (2017) derived a value of $\lambda_{\text{OMC-1}} = 0.41$.
In the following, we investigate how the polarization degree and angle, measured with SOFIA/HAWC+, change with cloud properties, namely, the column density and temperature. For this purpose, we follow Chuss et al. (2019) to construct column density, temperature, and dust emissivity maps.

Data preparation

In order to derive the column density, temperature, and dust emissivity maps, we used the SOFIA/HAWC+ 154 \( \mu \)m and 214 \( \mu \)m data, together with JCMT/SCUBA-2 850 \( \mu \)m and Herschel PACS 70 \( \mu \)m and 160 \( \mu \)m data. We re-projected all data to the pixel scale of the measurement of 214 \( \mu \)m. In the next step, we beam-convoluted the 70, 154, 160, and 850 \( \mu \)m data to the corresponding resolution of HAWC+ band E (214 \( \mu \)m) of 18.2\( '' \).

Fitting routine

We fit a single-temperature modified blackbody function to each pixel:

\[
I_v = (1 - \exp(-\tau_v)) B_v(T).
\]  

Here, \( B_v(T) \) describes the Planck function and \( \tau_v \) the optical depth:

\[
\tau_v = \epsilon \left( \frac{\nu}{\nu_0} \right)^\beta,
\]

where the quantity \( \beta \) is the dust emissivity index and \( \nu_0 \) a reference frequency. The parameter \( \epsilon \) is a scaling factor related to the column density \( N(H_2) \):

\[
\epsilon = \kappa_{H_2} \mu m_H N(H_2).
\]

Here, \( \kappa_{H_2} \) is the reference dust opacity per unit mass, \( m_H \) the atomic mass of hydrogen, and \( \mu \) the mean molecular weight per hydrogen atom. We set \( \nu_0 \) to 1000 Hz and adopt \( \kappa_{H_2} \) (1000 Hz) = 0.1 cm\(^2\) g\(^{-1}\). The final resulting fit function is:

\[
I_v = \left( 1 - \exp\left( -\kappa_{H_2} \mu m_H N(H_2) \left( \frac{\nu}{\nu_0} \right)^\beta \right) \right) \frac{2\hbar \nu^3}{c^2} \frac{1}{\exp\left( \frac{h \nu}{k T} \right) - 1}.
\]

The fit parameters are the column density \( N(H_2) \), the temperature \( T \), and the dust emissivity index \( \beta \). We adopted the uncertainties for the Stokes I data given in Chuss et al. (2019) and rejected all fitted pixels with a reduced \( \chi^2 \) (used to estimate the goodness of the fit) greater than 10. The resulting maps of column density, temperature, and dust emissivity index are shown in Fig. 5.

The dust emissivity index \( \beta \) is lowest at the central regions of OMC-3 and increases toward the outer regions, indicating potential dust grain growth at regions with higher density and in the vicinity of stellar sources. The mean dust emissivity index amounts to \( \beta = 1.72 \). With this type of fitting technique, it is often omitted that beta is a free parameter (e.g., Gandilo et al. 2016; Santos et al. 2019). Santos et al. (2019) used a fixed value of \( \beta = 1.62 \) for \( \rho \) Oph A, while Gandileo et al. (2016) applied \( \beta = 2.0 \) for the Vela C molecular cloud. These fixed values are similar to our derived mean value.

In the maps shown in Fig. 5, we mark the known stellar sources (white/black star signs; from Chini et al. 1997). The embedded stellar sources radiate and heat the surrounding dust, that is, the position of stellar sources is closely connected to an increased temperature. The highest temperature can be found in the vicinity of MMS6, the most luminous source in OMC-3 (Matthews et al. 2005; Takahashi et al. 2009). The only exception where the position of a stellar source is not related to an increased temperature is MMS4 at R.A.: 5h 35m 20.5s, Dec.: -5\( ° \). One possible explanation for this sole exception is the optical depth, which is highest at this stellar position (see Fig. B.1 in the Appendix). The mean temperature \( T = 28.38 \text{ K} \). The column density is highest around MMS4 with \( N(H_2)_{\text{max}} = 5.15 \cdot 10^{22} \text{ cm}^{-2} \). The mean column density amounts to \( N(H_2) = 1.10 \cdot 10^{22} \text{ cm}^{-2} \).

### Table 1. Overview of the properties in relation to the Chandrasekhar-Fermi method for the calculation of the magnetic field strength of OMC-3.

| Parameter                             | Symbol | Value            |
|---------------------------------------|--------|------------------|
| Hydrogen column density               | \( N(H_2) \) | \((1.70 \pm 1.0) \cdot 10^{22} \text{ cm}^{-2}\) |
| Hydrogen volume density               | \( n(H_2) \) | \((3.81 \pm 2.24) \cdot 10^4 \text{ cm}^{-3}\) |
| Angular dispersion (154 \( \mu \)m)  | \( \sigma_{154,\mu m} \) | 11.24\(^{+0.92}_{-0.75}\) deg |
| Angular dispersion (214 \( \mu \)m)  | \( \sigma_{214,\mu m} \) | 8.68\(^{+0.83}_{-0.70}\) deg |
| Velocity dispersion                  | \( \Delta v \) | 0.98 km \( \text{s}^{-1}\) |
| POS magnetic field strength (154 \( \mu \)m) | \( B_{\text{pos},154,\mu m} \) | 158.6\(^{+58.9}_{-63.3}\) \( \mu \)G |
| POS magnetic field strength (214 \( \mu \)m) | \( B_{\text{pos},214,\mu m} \) | 205.4\(^{+82.0}_{-83.6}\) \( \mu \)G |
| Total magnetic field strength (154 \( \mu \)m) | \( B_{154,\mu m} \) | 201.9\(^{+75.0}_{-80.6}\) \( \mu \)G |
| Total magnetic field strength (214 \( \mu \)m) | \( B_{214,\mu m} \) | 261.4\(^{+104.4}_{-106.4}\) \( \mu \)G |

### Notes

* Aso et al. 2000

#### 3.3. Correlation between magnetic field structures and cloud properties

Polarimetric observations of star-forming regions often show a decreasing degree of polarization with increasing density, making up so-called "polarization holes" (e.g., Henning et al. 2001; Wolf et al. 2003; Chuss et al. 2019; Zielinski et al. 2021). We investigate how the polarization degree changes in relation to the column density derived above. As in the data preparation shown...
Fig. 5. Maps of column density (top left), temperature (top right), dust emissivity index (bottom left), and the corresponding reduced $\chi^2$ (bottom right). The beam size of 18.2′′ (band E, 214 $\mu$m) is indicated in the lower right for each figure.

in Sect. 3.3, the Stokes parameter $Q$ and $U$ at 154 $\mu$m are re-projected and beam-convolved to 214 $\mu$m resolution as well. The polarization degree is then calculated using

$$p = \frac{\sqrt{Q^2 + U^2}}{I}.$$ (12)

Our results for 154 $\mu$m and 214 $\mu$m are shown in Fig. 6.

For both wavelengths, the polarization degree decreases from $\sim$ 10% to $\lesssim$ 1% with increasing density. Inspired by the work of Davis et al. (2000), who applied linear least-square fits to polarimetric observations of the Serpens cloud core and found a correlation between the measured polarization and intensity, Henning et al. (2001) found a correlation between these quantities in the case of the two Bok globules CB54 and DC253-1.6 as well. They approximated the decrease in the polarization degree as a function of increasing intensity using the following equation:

$$p = a_0 + a_1 \cdot \left( \frac{I}{I_{\text{max}}} \right)^{a_2},$$ (13)

where $a_0$, $a_1$, and $a_2$ are fitting parameters. We applied the same technique, but refer to the column density instead of intensity. Therefore, the subsequent results are comparable. For our case we apply

$$p = a_0 + a_1 \cdot \left( \frac{N(H_2)}{N(H_2)_{\text{max}}} \right)^{a_2}.$$ (14)

We obtained $a_{0,154\mu m} = -0.53 \pm 0.24$, $a_{1,154\mu m} = 1.58 \pm 0.20$, $a_{2,154\mu m} = -0.51 \pm 0.04$ and $a_{0,214\mu m} = 0.44 \pm 0.16$, $a_{1,214\mu m} = 0.81 \pm 0.12$, $a_{2,214\mu m} = -0.63 \pm 0.05$. The parameter $a_2$, which describes the slope of the curve, is slightly higher at 214 $\mu$m. Interestingly, comparing this slope to those reported in the previous studies for Bok globules, a different object class, one can see that the slopes are similar. For the Bok globule B335, Wolf et al. (2003) derived $a_{2,850\mu m} = -0.43$ with JCMT/SCUBA and Zielinski et al. (2021) derived $a_{2,214\mu m} = -0.55$ with SOFIA/HAWC+. Furthermore, the calculated slope for the Bok globule CB54 is $a_{2,850\mu m} = -0.64$ (Henning et al. 2001) and $a_{2,850\mu m} = -0.55$ for DC 253-1.6 (Henning et al. 2001). See Table 2 for an overview of all calculated $a_2$ values. There are multiple possible reasons for the occurrence of polarization holes. Since the slope is similar for different object classes and wavelengths, this may be a hint that the same effects are responsible. However, this needs further investigation, since the spatial scale on which the polarization hole in OMC-3 is examined is larger than that of the Bok Globule studies mentioned above.
Table 2. Calculated values for the parameter $a_2$ that describes the slope of the polarization hole at different wavelengths.

| Object | Wavelength | Instrument | $a_2$ | Reference |
|--------|------------|------------|-------|-----------|
| OMC-3  | 154 $\mu$m | SOFIA/HAWC+ | -0.51 | this paper |
| OMC-3  | 214 $\mu$m | SOFIA/HAWC+ | -0.63 | this paper |
| B335   | 214 $\mu$m | SOFIA/HAWC+ | -0.55 | Zielinski et al. (2021) |
| B335   | 850 $\mu$m | JCMT/SCUBA  | -0.43 | Wolf et al. (2003) |
| CB54   | 850 $\mu$m | JCMT/SCUBA  | -0.64 | Henning et al. (2001) |
| DC 253-1.6 | 850 $\mu$m | JCMT/SCUBA  | -0.55 | Henning et al. (2001) |

Fig. 6. Polarization degree at 154 $\mu$m (top) and 214 $\mu$m (bottom) as a function of the column density, scaled to the maximum value.

3.3.2. Polarization hole in OMC-3

The SOFIA/HAWC+ observations show a decrease of the polarization degree toward dense regions of OMC-3. As mentioned above, there are several existing hypotheses that are aimed at explaining this phenomenon, such as an insufficient angular resolution of a possibly complex magnetic field structure on scales below the resolution of the polarization maps (e.g., Shu et al. 1987; Wolf et al. 2004), a disruption of spinning large grains into smaller fragments (radiative torque disruption, Hoang et al. 2019; Hoang 2019), or certain combinations of optical depth, dust grain size, and chemical composition (Brauer et al. 2016). What is particularly interesting for our purposes is the latter proposal. Brauer et al. (2016) showed that a polarization hole can occur as a result of the superposition of polarized emission and dichroic extinction, which act as counteracting mechanisms. This effect may even cause a flip in the polarization direction by 90°, if the dichroic extinction dominates over dichroic emission (Reissl et al. 2014; Brauer et al. 2016). Indeed, Liu (2021) showed this 90° flip for OMC-3 (MMS6) with a comparison of 1.2 mm ALMA and 9 mm JVLA polarimetric observations, see Fig. 8. They find that the innermost ~ 100 au region of OMC-3 (MMS6) is optically thick at 1.2 mm and optically thin at 9 mm.

Given a moderate optical depth, the counteracting mechanisms of polarized emission and absorption result in a decrease of the polarization degree. However, this effect can only be applied to explain the polarization hole in the innermost area of OMC-3. The reason for the decrease in the degree of polarization in the outer areas is unknown. The polarimetric ALMA observation shows that the magnetic field in OMC-3 is more complex on smaller scales. Due to beam-averaging, an unresolved and more complex magnetic field would lead to a lower degree of polarization. While the optical depth seems to have an effect on the decrease in the polarization degree, we cannot rule out a potential influence of the magnetic field complexity. However, other effects, such as the radiative torque disruption (Hoang et al. 2019; Hoang 2019) or less-aligned dust grains at higher densities (Goodman et al. 1992; Creese et al. 1995), along with their contribution to the polarization hole, cannot be ruled out.

3.3.3. Degree of polarization versus temperature

In Fig. 8, we show the obtained polarization degrees at 154 $\mu$m and 214 $\mu$m as a function of the derived temperature. The temperature is strongly correlated with the position of stars. The degree of polarization drops sharply in the vicinity of the stars, while the degree of polarization is higher in colder regions.
3.3.4. Polarization spectrum versus column density and temperature

In the next step, we investigate how the polarization spectrum, that is, the polarization degree as a function of wavelength, changes with column density and temperature of OMC-3. We define the polarization spectrum as \( p_{214\mu m}/p_{154\mu m} \), similar to Santos et al. (2019), who studied the polarization spectrum of \( \rho \) Oph A and Michail et al. (2021), who studied the polarization spectrum of OMC-1. Using this definition, \( p_{214\mu m}/p_{154\mu m} < 1 \) indicates a negative spectral slope and \( p_{214\mu m}/p_{154\mu m} > 1 \) a positive spectral slope. We calculated the polarization spectrum for all pixels where we have valid data for the polarization degrees at both wavelengths, namely, those data meeting criteria 2 and 3, and valid data for the column density and temperature.

The spatially resolved map of \( p_{214\mu m}/p_{154\mu m} \) is shown in Fig. 9. In the southern and eastern part of OMC-3, the polarization spectrum is smaller than 1, while in the central and northern part the spectrum is mostly greater than 1. The ratio of \( p_{214\mu m}/p_{154\mu m} \) versus column density and temperature is shown in Fig 10 (top) and Fig. 10 (bottom), respectively. In our maps, we find a slightly larger number of data points with a negative slope (878) than with a positive slope (709). The mean polarization slope is slightly negative (\( p_{214\mu m}/p_{154\mu m} = 0.93 \pm 0.24 \)), indicating a relatively flat slope of the polarization spectrum. We do not find a clear correlation between polarization spectrum and column density. However, it does appear that the polarization spectrum is particularly flat (\( \sim 1 \)) at higher column densities (see Fig. 10 top). The polarization spectrum is smaller than 1 for low (\( \leq 25 \) K) and high (\( \geq 42 \) K) temperatures. However, in these cases the sample size is small if compared to the total number of data points. Therefore, no significant conclusion about the connection between the polarization ratio and the derived temperature is possible.

In contrast, Michail et al. (2021) find a positive correlation between the slope of the polarization spectrum and the temperature of OMC-1. However, they report no significant correlation between slope and column density. In contrast, Santos et al. (2019) report a clear correlation between polarization spectrum and column density and temperature in \( \rho \) Oph A.
4. Magnetic field of OMC-3 derived from observations in different wavelength ranges

OMC-3 is a well studied object with polarimetric observations ranging from the far-infrared to submm and mm. In the following, we compare these observations to the SOFIA/HAWC+ observation at 154 and 214 μm (see Fig. 11).

350 μm: Houde et al. (2004) observed OMC-3 with SHARC II/Hertz at 350 μm. These authors reported a mean polarization angle of $\bar{\phi} = -33^\circ \pm 9^\circ$ for OMC-3 MM1-6. If we limit our observations to the same region, we obtain $\bar{\phi} = -34^\circ \pm 12^\circ$ and $\bar{\phi} = -34^\circ \pm 10^\circ$ at 154 μm and 214 μm, respectively. The Stokes averaged polarization degree at 350 μm amounts to $p_{350}\mu m = 1.55\% \pm 0.12\%$. For the same region we obtain $p_{154}\mu m = 3.2\% \pm 1.71\%$ and $p_{214}\mu m = 2.86\% \pm 1.35\%$. While the polarization angles are well aligned at 154 μm, 214 μm, and 350 μm, the polarization degree is 1.2% lower at 350 μm. The rather small standard deviation of the polarization degree at 350 μm indicates that the polarization hole is not as prominent as it is at 154 and 214 μm.

850 μm: Matthews et al. (2001) observed OMC-3 with JCMT/SCUBA at 850 μm. The reported polarization angles are well aligned with our results. The mean polarization degree at 850 μm is 5.0%, including the observation at the southern regions (MM57-10, see Fig. 11, top-right). This mean polarization degree is similar to our results, 4.8±2.7% and 3.8±2.0% for 154 and 214 μm, respectively. The 850 μm observation shows a polarization hole for OMC-3 as well.

1.2 mm & 9 mm: Liu (2021) observed OMC-3 with ALMA/JVLA at 1.2 and 9 mm. These high-resolution observations show that the polarization angles have a more complex pattern at small scales than they have at larger scales. Since SOFIA/HAWC+ does not allow resolving these structures, we do not compare the polarization degrees.

The magnetic field structure, which is derived from the SOFIA/HAWC+ observations, is consistent with the magnetic field, which was reported from previous polarimetric observations in the far infrared and submm wavelength range. While the magnetic field appears uniform at larger scales, it shows a greater level of complexity on small scales.

5. Conclusions

We investigated the magnetic field of OMC-3 based on polarimetric observations with SOFIA/HAWC+ at 154 μm and 214 μm.

1. The polarization maps of OMC-3 at 154 μm (band D) and 214 μm (band E) show a uniform pattern, parallel to the filament for both wavelengths. The mean polarization angles are $\bar{\theta}_{154}\mu m = -32.6^\circ \pm 14.5^\circ$ and $\bar{\theta}_{214}\mu m = -24.1^\circ \pm 20.4^\circ$ for 154 μm and 214 μm, respectively. These results are consistent with previous polarimetric observations of OMC-3 in the far-infrared and submm wavelength range (Matthews et al. 2001; Houde et al. 2004).

2. The mean polarization degree amounts to $p_{154}\mu m = 4.8\% \pm 2.7\%$ and $p_{214}\mu m = 3.8\% \pm 2.0\%$ at 154 μm and 214 μm, respectively. The polarization degree decreases for both wavelengths toward regions with increased column density. An unequivocal explanation for the occurrence of this “polarization hole” could not be found. However, the “optical depth effect”, namely, the superposition of polarized emission and dichroic extinction seems to be of importance in the innermost densest regions, consistent with the observed 90° flip of the polarization vectors that has been observed using ALMA and JVLA.

3. The magnetic field of OMC-3 is uniform and perpendicular to the filament for both wavelengths. We calculated a magnetic field strength of 202 μG at 154 μm and 261 μG at 214 μm.

4. We do not find a general correlation between the polarization spectrum ($p_{214}\mu m/p_{154}\mu m$) and cloud properties, that is, column density N(H$_2$) and temperature T. These results are in contrast to previous studies of similar objects (Santos et al. 2019; Michail et al. 2021).

5. The large-scale magnetic field structure and strength are consistently derived from observations that cover a wide range of wavelengths, that is, the far infrared to submm. On small scales, the magnetic field appears to be more complex.

Using SOFIA/HAWC+ we obtained new multiwavelength polarimetric observations of the filamentary structure OMC-3 at 154 μm and 214 μm. These observations reveal a uniform magnetic field, which is oriented perpendicular to the filament. These findings are in good agreement with previous observations at similar scale. No correlation between the polarization spectrum and cloud properties of OMC-3 has been found.

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Fig. 11. Multiscale, multiscale polarization maps of OMC-3. Top left: Intensity and polarization map obtained with SHARC II and Hertz at 350 µm, respectively. Overlaid are polarization vectors in white and black (Houde et al. 2004, ©AAS. Reproduced with permission). Top right: Total intensity, observed at 850 µm with SCUBA, is shown with overlaid polarization vectors in blue (Matthews et al. 2001, ©AAS. Reproduced with permission). Bottom left: Total intensity, observed at 1.2 mm with ALMA, is shown with overlaid polarization vectors in blue. Red polarization vectors are observed with JVLA at 9 mm (Liu 2021, ©AAS. Reproduced with permission). Bottom right: Total intensity, observed at 214 µm with SOFIA/HAWC+, is shown with overlaid polarization vectors in blue.

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Appendix A: Polarization map of OMC-3

Fig. A.1. Complete SOFIA/HAWC+ band D (154 µm, left) and E (214 µm, right) polarization maps of OMC-3. The total intensity is shown with overlaid polarization vectors in blue. The length of the vectors is proportional to the polarization degree and the direction gives the orientation of the linear polarization. The isocontour lines mark 20, 40, 60, and 80% of the maximum intensity. According to criteria (2) and (3) only vectors with \( I > 100 \sigma_I \) and \( p > 3 \sigma_p \) are considered (see Sect. 2). The beam size of 13.6\arcsec{} for band D and 18.2\arcsec{} for band E (defined by the FWHM) are indicated on the lower-right.
Appendix B: Optical depth map of OMC-3 at 154, 160, 214, and 850 µm

Fig. B.1. Maps of optical depth at wavelengths of 154 µm (top left), 160 µm (top right), 214 µm (bottom left), and 850 µm (bottom right). The contour lines mark 10, 20, 30, 40, 50, 60, 70, 80, and 90 % of the maximum optical depth for each wavelength. The white asterisk symbols mark known stellar sources (Chini et al. 1997). The beam size of 18.2'' (band E) is indicated on the lower-right of each figure.