Large & small-scale magnetic fields in star-forming regions

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Introduction

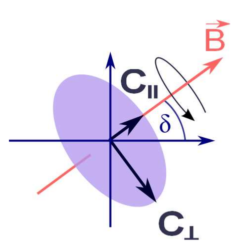
We present numerical and observational studies aimed at analyzing the potential of multi-wavelength high-spatial resolution continuum polarization measurements for constraining the multi-scale structure of magnetic fields in the interior and environment of molecular clouds.

I. NUMERICAL SIMULATIONS

We developed an extended, adaptive grid version of the 3D Monte-Carlo radiation transfer code MC3D (Wolf 2003) for multi-wavelength polarization simulations. On the basis of theoretical dust grain models, polarization due to dichroic extinction and reemission as well as scattering is considered. Multi-scale magneto-hydrodynamical (MHD) simulations of the interstellar medium (ISM) provide the complex distributions of the density, temperature, and magnetic field in star-forming regions. This type of sophisticated synthetic polarization modeling will allow us to prepare and properly analyze existing and future observations of the three-dimensional magnetic field structure in the ISM. Various kinds of dust grain properties and advanced MHD scenarios are considered to cover the broad variety of observable ISM characteristics.

I.1. Radiative Transfer

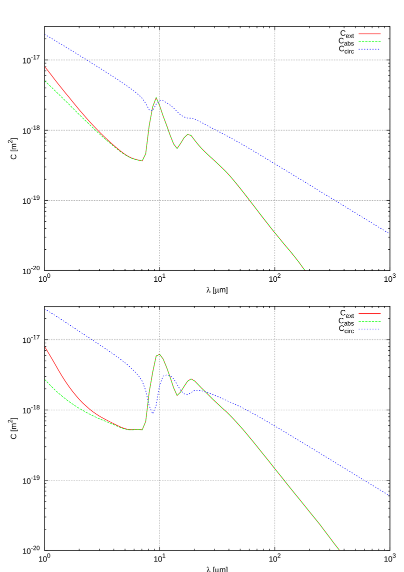
By applying the Stokes - vector formalism one obtains the radiative transfer equation in matrix form to calculate the dichroic polarization effects (Whitney & Wolff 2002). To implement these effects of aligned non-spherical dust grains in the ISM we assumed a constant number density n along each path length ds. The particles are considered to be perfect black body radiators with distinct reemission, extinction and alignment characteristics (Imperfect Davis-Greenstein (IDG) alignment; Voshchinnikov 1989).



$$\frac{d}{nds}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = -\begin{pmatrix} C_{ext} & \Delta C_{ext} & 0 & 0 \\ \Delta C_{ext} & C_{ext} & 0 & 0 \\ 0 & 0 & C_{ext} & -\Delta C_{circ} \\ 0 & 0 & \Delta C_{circ} & C_{ext} \end{pmatrix}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} + \begin{pmatrix} C_{abs}B_\lambda(T) \\ \Delta C_{abs}B_\lambda(T)cos(2\delta) \\ \Delta C_{abs}B_\lambda(T)sin(2\delta) \\ 0 \end{pmatrix}$$

The cross sections vary with incident and polarization angles of the passing light. Subsequently, dichroic extinction and thermal reemission mechanisms lead to linear as well as circular polarization. Therefore, the polarized light carries with it the information about the projected configuration of the magnetic field along the line of sight.

I.2. Dust Model

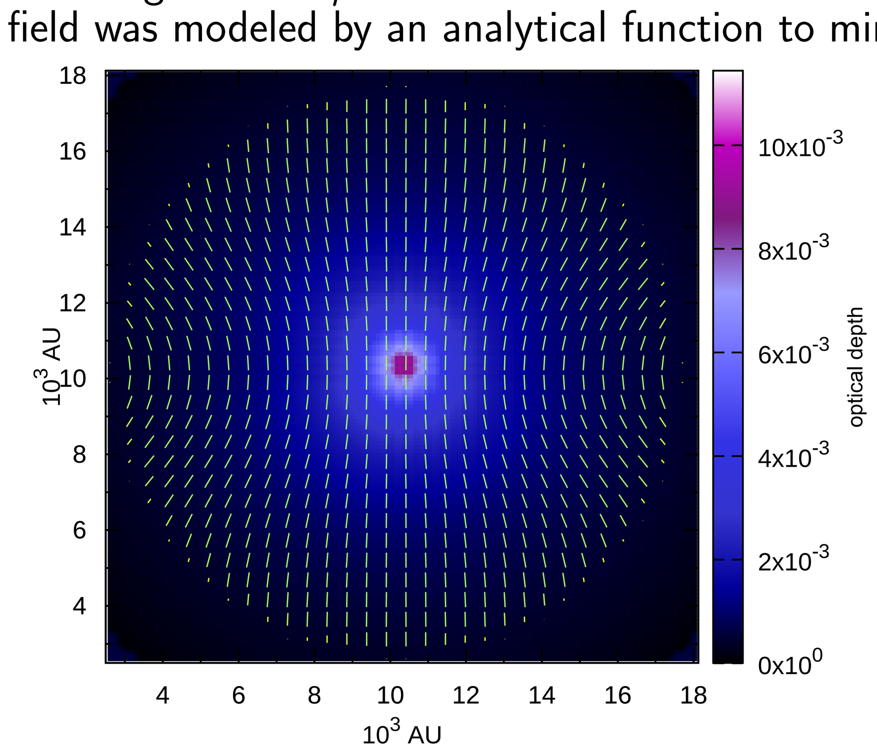


Interstellar dust grains can be a composite collection of materials and complex shapes. We obtain the parameter of the grains using the Discrete Dipole Approximation DDA. The idea behind this approximation is to model the shape of the dust grains with a distinct number of dipoles. We use the well tested program DDSCAT 7.2 (Draine & Flatau 2012) to calculate the required cross sections.

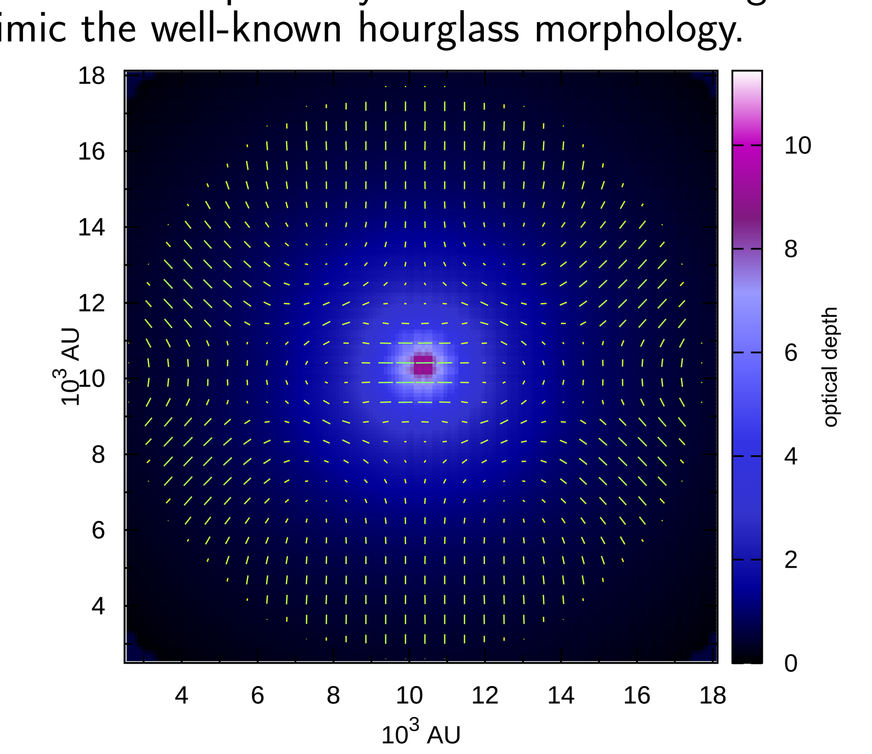
*Cross sections for oblate grains with an aspect ratio of 0.5 in a wavelength range of $1\mu m - 10^3\mu m$ in parallel (**top**) resp. perpendicular (**bottom**) to the symmetry axis. All values are weighted means over a range of effective radii ($n(a) \propto a^{-3.5}, a \in [5nm - 250nm]$). The materials are 62.5% silicate and 37.5% graphite. For graphite we apply the common "1/3 - 2/3" approximation.*

I.3. Results

To demonstrate the accuracy and potential of the extended MC3D code we assumed a spherical Bonnor – Ebert profile with a central temperature of $T_0 = 50K$, an increasing density n_0 and a wavelength of $164\mu m$. Inner and outer radii are $500AU$ respectively $20627AU$. The magnetic field was modeled by an analytical function to mimic the well-known hourglass morphology.



Optically thin sphere with a central number density of $n_0 = 10^3 m^{-3}$. The polarization vectors follow the projected magnetic field lines due to dichroic absorption.



Optically thick sphere with a central number density of $n_0 = 10^6 m^{-3}$. Dichroic reemission becomes dominant and the hourglass morphology gets distorted.

II. POLARIMETRY OF BOK GLOBULES

Bok globules represent an ideal environment to study the influence of magnetic fields on the process of low-mass star formation. The magnetic field strength and structure in the dense inner regions of the globules can be determined by observing the polarized reemission radiation of aligned dust grains in the sub-mm wavelength range. The magnetic field in the outer, less dense parts of the globules can be traced by observing polarized radiation of background stars in the optical or near-IR. We present polarimetric observations of two Bok globules, CB68 and B335, carried out in the near-IR (ISAAC/VLT) and in the optical (IFOSC/IGO). Together with archival sub-mm data (SCUBA/JCMT), we trace the magnetic fields in these objects from 10^3 AU scales up to $10^5 - 10^6$ scales for the first time.

II.1. Target selection and observations

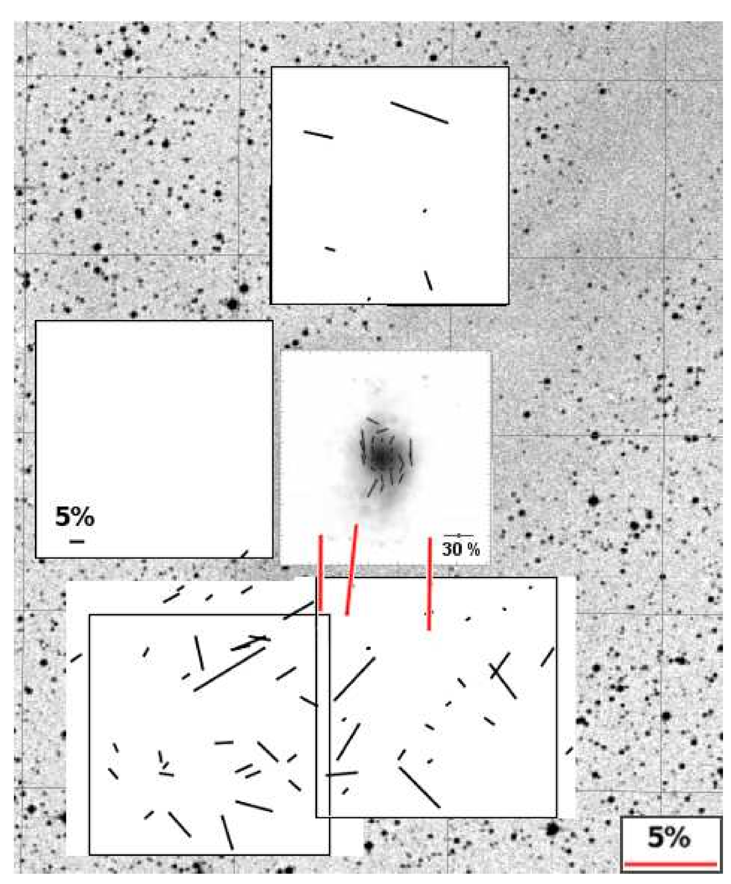
Selection criteria:

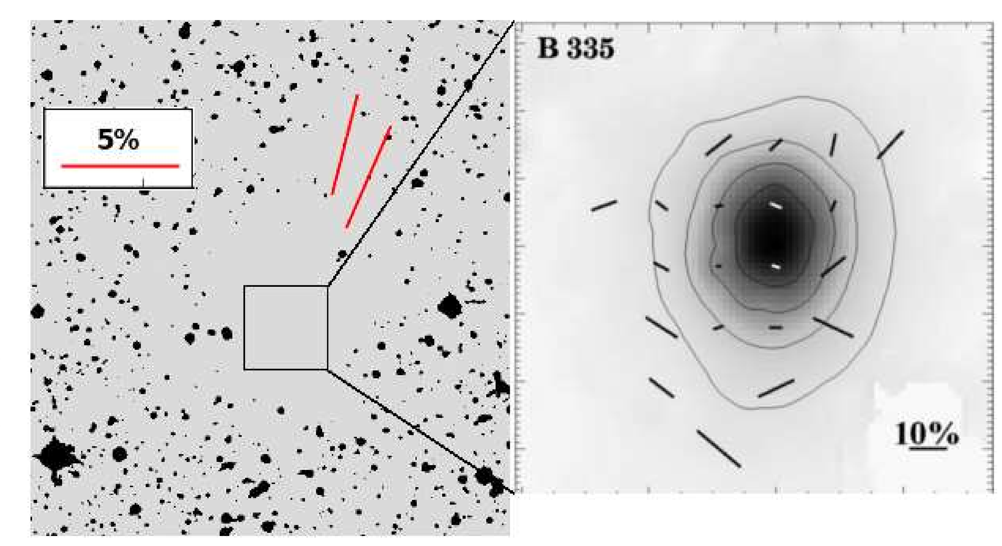
- Isolated and compact globules
- Available sub-mm maps
- Regular magnetic field structure in the sub-mm

Observations:

- Near-IR, Js band: Infrared Spectrometer and Array Camera (ISAAC) at Very Large Telescope (VLT)
- Optical, R band: IUCAA Faint Object Spectrograph & Camera (IFOSC) at IUCAA Girawali Observatory (IGO)

II.2. Polarization maps of CB68 and B335





Top: B335. *Left: Composite map: near-IR (red vectors, $P > 3\sigma_P$, ISAAC/VLT, this work), DSS map (back). Right: Sub-mm (SCUBA/JCMT, Wolf et al. 2003).*
Left: CB68, *composite map: sub-mm (center, SCUBA/JCMT, Vallée et al. 2003), optical (outer boxes, IFOSC/IGO, this work), near-IR (red vectors, $P > 3\sigma_P$, ISAAC/VLT, this work), DSS map (back).*

The optical data of CB68 matches the whirl-like structure seen in the sub-mm map with an arm coming from the top to the center and another arm going from the center to the bottom left. The near-IR data for both, CB68 and B335, fits well in terms of the polarization degree but is under-determined in terms of the polarization angle. For details see II.3.

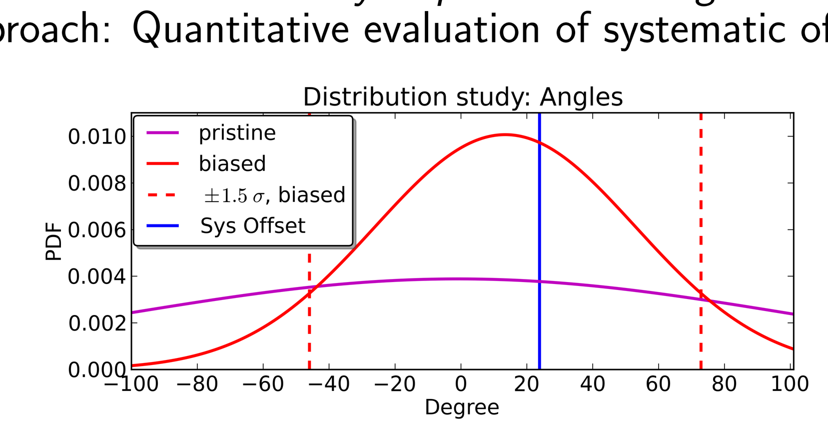
II.3. Discussion

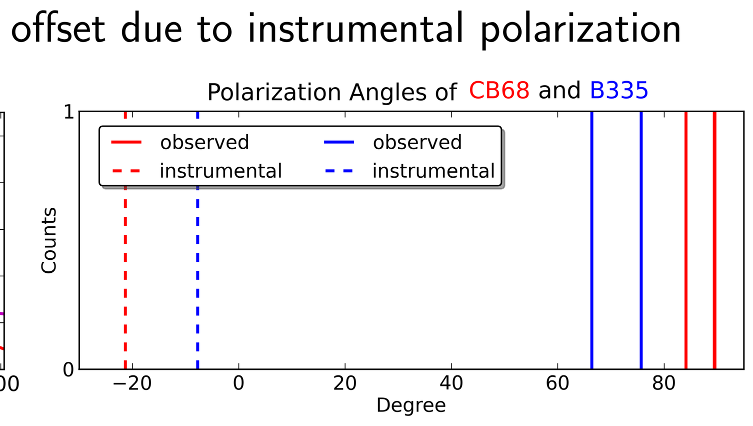
Observations:

- Significant polarization in the outer, less dense parts of CB68 and B335 in the optical and near-IR
- Indication of connection between the structure in the inner and outer part of CB68

Data analysis:

Discussion of uncertainty of polarization angle
Approach: Quantitative evaluation of systematic offset due to instrumental polarization





Left: *Influence of systematic offset on a given distribution. Large difference between observed angle and systematic offset ($\sim 60°$): High probability for low impact of instrumental polarization.*
Right: *The measured IR polarization lies above this threshold.*

References

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