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THE ORIGIN OF DUST POLARIZATION IN THE ORION BAR

V. J. M. Le Gouellec[1] and B.-G. Andersson[1]

Abstract. The linear polarization of thermal dust emission provides a powerful tool to probe interstellar and circumstellar magnetic fields, because aspherical grains tend to align themselves with magnetic fields lines. However, while the Radiative Alignment Torque (RAT) theory provides a quantitative framework for the understanding of this phenomenon, some aspects of this grain alignment mechanism still need to be quantitatively tested. One such aspect is the possibility that the reference direction for the alignment may change from the magnetic field ("B-RAT ") to the radiation field k-vector ("k-RAT ") in areas of strong radiation fields, such as the regions affected by massive star formations feedback mechanisms. Currently, the poor understanding of the B- to k-RAT transition precludes the opportunity of making reliable measurements of the magnetic fields, and thus magnetic field support, toward HII regions or PDRs, for example. In order to provide a well-characterized prototypical system to compare to ab initio RAT theory, our work focuses on investigating this grain alignment transition toward the Orion Bar that undergoes intense irradiation from the trapezium cluster, the most massive O-type star in the cluster, with multi-wavelength SOFIA HAWC+ chop-nod and scan-pol dust polarization observations. The aim is to quantify to what extent the k-RAT mechanism could contribute to the polarization, and to extrapolate our conclusions to other regions of similar conditions. From our estimation of the radiation field and volume density, we can predict the grain size above which this alignment transition can occur. However, we also discuss the rotational grain disruption of grains, that potentially takes place on the irradiated edge of the bar. We conclude that most grains should be rotationally disrupted before they could reach the typical size after which the alignment shifts from B-RAT to k-RAT.

Keywords: ISM: photon-dominated region (PDR) - ISM: magnetic fields -ISM: dust, extinction - polarization - radiative transfer

1 Introduction

Photodissociation or photon-dominated regions (PDRs) designate the regions of the interstellar medium (ISM) affected by the radiation produced by massive stars (Tielens & Hollenbach 1985). They harbor a variety of radiation driven chemical and physical processing, for which interstellar dust grains have a major role (see Wolfire et al. 2022, and references therein). Small and large grains absorb one part of the intense far-UV (FUV) radiation which gets radiated away as infra-red (IR) continuum. Besides very small grains and large molecules heat the gas via the photoelectric effect (Bakes & Tielens 1994; Weingartner & Draine 2001). The linear polarization of the dust thermal emission is a powerful tool to study those large grains. Paramagnetic grains, e.g., silicates, tend to align their minor axis with the ambient magnetic field via the Radiative Alignment Torque (RAT) mechanism (also called "B-RAT"; Draine & Weingartner 1996, 1997; Lazarian & Hoang 2007; Andersson et al. 2015). However, in the case of a strong anisotropic radiation field, the alignment axis can change from the magnetic field to the radiation field axis (also called "k-RAT"; Tazaki et al. 2017; Lazarian & Hoang 2007). Finally, intense radiation field can also trigger the RAdiative Torque Disruption mechanism (RATD, Hoang et al. 2019), which consist in the rotational disruption of grains. Firstly, our goal is to predict the preferred axis of alignment in order to determine whether polarized dust emission trace preferentially the magnetic field or the radiation field. Secondly, we study the effect of the irradiation on the population of aligned grains via the RATD effect to investigate whether it is an important dust evolution mechanism to take into account toward PDRs. Our study focuses on the Orion Bar, a PDR illuminated by the O7-type star θ^1 Ori C, the most luminous member of the Trapezium young stellar cluster (O'dell 2001).

[1] SOFIA Science Center, Universities Space Research Association, NASA Ames Research Center, Moffett Field, California 94035, USA

2 SOFIA HAWC+ observations

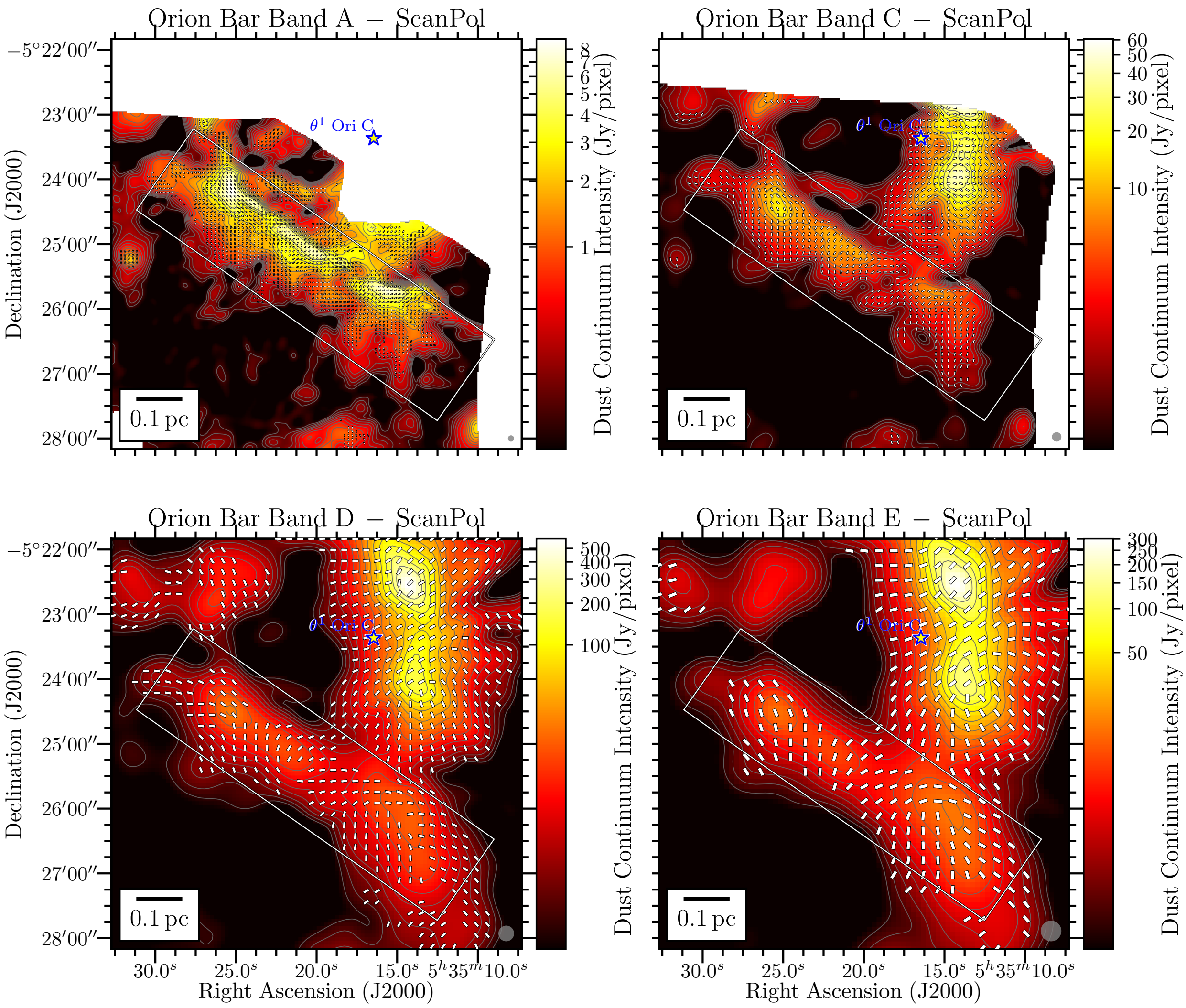

Fig. 1. Polarization maps of the Orion Bar, observed with SOFIA HAWC+ using the OTFMAP polarimetric mode at 53 μm (Band A, top left), 89 μm (Band C, top right), 154 μm (Band D, bottom left), and 214 μm (Band E, bottom right). Lines segments represent the magnetic field orientation, rotated by 90° from the E-vectors polarization angle maps. Vectors are plotted if $I/\sigma_I \geq 100$ and $P/\sigma_P \geq 5$. The length of the vectors does not represent any quantity. The color scale is the total intensity (Stokes I) of the thermal dust emission, shown from 35 σ_I. The black contours trace the dust continuum emission. The beam size is shown in the bottom right corner of each field. The position of the θ^1 Ori C star, the most luminous star of the Trapezium cluster, is indicated. The rectangular grey box shows the location of the Orion Bar and denotes the region that this paper is focusing on.

We have collected and analyzed SOFIA/HAWC+ polarimetric observations of the Orion Bar at four different wavelengths, i.e., 53, 89, 154, and 214 μm. Figure 1 presents the maps of the dust continuum emission overlaid with the polarization position angles showing the apparent magnetic field lines (rotating the polarization E-vectors by 90°) at these four wavelengths. The magnetic field exhibits a complex morphology. We note that different wavelengths may preferentially probe regions of different dust temperature conditions. Those regions may have different magnetic field geometries, thus contributing to the polarization angles disparities across wavelength. The polarization angle maps are overall consistent across wavelength, which suggests that no significant transition of grain alignment axis is occurring among the aligned dust grains.

3 The grain alignment conditions in the Bar

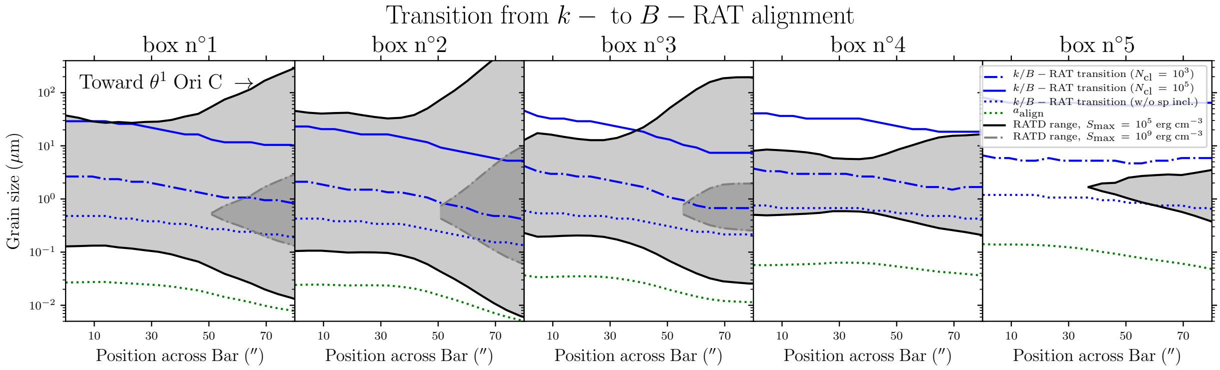

Fig. 2. Grain size corresponding to the k- to B-RAT transition as function of the position across the Orion Bar. In this Figure, the Orion Bar is divided in 5 boxes along its major axis such as box n°1 is the most northern one. In each panel, the x-axis is the position along the minor axis of the Orion Bar, with increasing values corresponding to closer location from θ^1 Ori C. For each position across the Orion Bar, the grain size at which the k- to B-RAT transition is occurring is found equalizing the radiative precession timescale with the Larmor precession timescale for a grain without super paramagnetic inclusions (blue dotted line), and for two values of number of iron inclusions N_{cl}, i.e., 10^3 and 10^5 (blue dot-dash and solid blue lines, respectively). The dotted green line is the minimum grain size of aligned grains a_{align}. The range of grain size affected by rotational disruption $a_{disr} - a_{disr,max}$, for two values of tensile strength $S_{max} = 10^5$ and $10^9\,\mathrm{erg\,cm^{-3}}$, are shown by the shaded region encompassed by the dark and grey lines, respectively.

In order to estimate the grain alignment conditions, we use the SED grey-body fit of Chuss et al. (2019) to retrieve the dust temperature and the density of the Bar at 18.7$''$ angular resolution. This allows us to calculate a_{align}, the minimum size of aligned grains, a_{disr} and $a_{disr,max}$, the grain size range inside which dust grains are rotationally disrupted by RATD (this depends on the grains' tensile strength S_{max}), and a_{trans}, the grain size at which the B- to k-RAT transition occurs (grains larger than a_{trans} are k-RAT aligned). We present these parameters as a function of the position across the Bar in Figure 2. We find that k-RAT is not the dominant grain alignment mechanism in the Orion Bar because the grains whose size are above the typical grain size a_{trans} correspond to grains too large to be the dominant source of polarized dust emission. In addition, those grains would likely be rotationally disrupted before they could reach this typical size.

4 Conclusions

We conclude that the k-RAT grain alignment mechanism is not the dominant cause of dust polarization in the Orion Bar. The grains potentially aligned via k-RAT would be too large given the local physical conditions of the Bar, or already rotationally fragmented by the RATD mechanism. In addition, while the impact of RATD seems to be moderate throughout the Bar given the average degree of polarization and evolution of the polarization fraction as a function of the radiation conditions, we suggest that it could still be an active factor of dust grain evolution in PDRs, controlling the size distribution of the large aligned dust grains.

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