LIPS III: The Large Interstellar Polarisation Survey

Observational constraints on grain structures and alignment efficiencies

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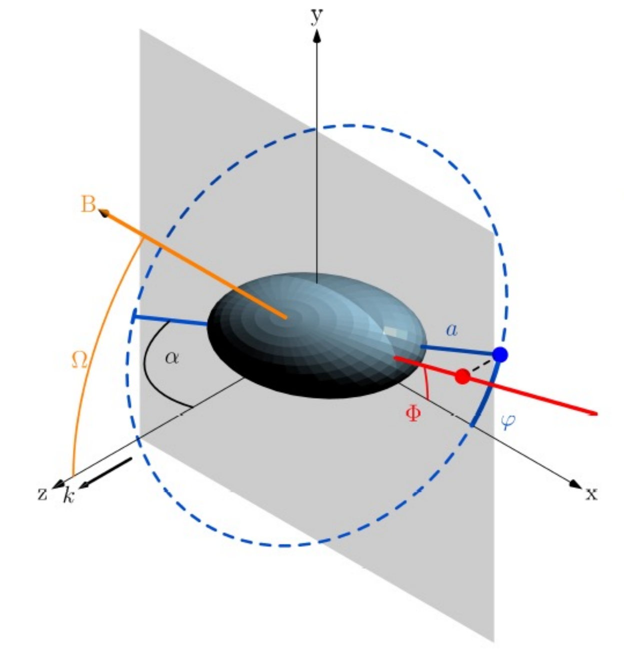


Figure: Geometry of a perfectly aligned spinning prolate grain. The line of sight is the z-axis. The magnetic field lies in the y–z plane at inclination angle Ω to the line of sight. The grain spins around B within a plane perpendicular to the field. The grain symmetry axis and its rotation angle relative to the sky plane are indicated.

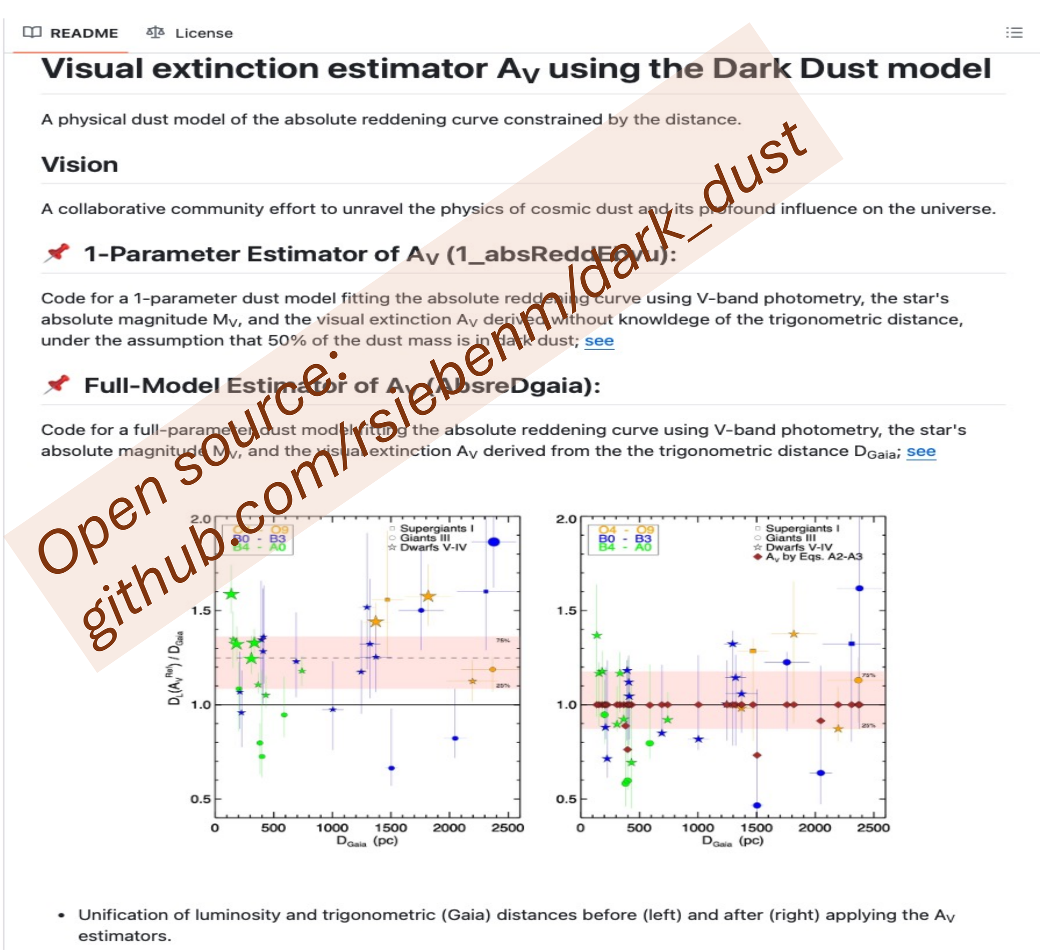
LIPS: The Large Interstellar Polarisation Survey (LIPS) obtains FORS/VLT spectro-polarimetry in the wavelength range 0.38–0.92 µm for 161 sightlines through the diffuse interstellar medium.

Sample: The LIPS sample was selected based on the availability of reddening curves: in the far-UV from the IUE and FUSE satellite missions, in the optical from ground-based photometry, and in the near-infrared from 2MASS. High-resolution spectra were obtained with UVES/VLT to verify the spectral types and luminosity classes of the stars used to derive the reddening curves, and to assess the number of clouds along each sightline. Distance Unification: Gaia parallaxes were used to estimate the visual extinction required to reconcile the luminosity distances with the trigonometric distance estimates for the same stars (Siebenmorgen et al. 2025): Av = V − Mv − 5 log(Dgaia) + 5.

Distance unification: The luminosity distance estimate to stars provides an overestimate when compared to the trigonometric distance. Gaia parallaxes were used to estimate the visual extinction required to reconcile the luminosity distances with the trigonometric distance estimates (Siebenmorgen et al. 2025):

$$Av = V - Mv - 5\log(D_{Gaia}) + 5.$$

Planck Observations: The dichroic polarisation spectra were complemented with Planck 850 µm polarimetry. Three sightlines in the sample show both significant starlight polarisation and Planck thermal emission polarisation, with comparable extinction values, and the expected 90-degree rotation in polarisation angle between absorption and emission. These sightlines provide an almost orthogonal observational constraint on the aligned grains, allowing limits to be set on particle shape, porosity, and alignment efficiency. A consistent fit to all three sightlines is obtained using Radiative Alignment Torque (RAT) alignment theory. Silicate grains with radii greater than ~100 nm are found to be perfectly aligned. Carbonaceous grains are either randomly aligned or partially (50%) aligned. Models assuming ferromagnetic inclusions in carbon grains or imperfect Davis-Greenstein alignment do not reproduce the data.



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Visual extinction estimator A_V using the Dark Dust model

A physical dust model of the absolute reddening curve constrained by the distance.

Vision

A collaborative community effort to unravel the physics of cosmic dust and its profound influence on the universe.

1-Parameter Estimator of A_V (1_absReddEovu):

Code for a 1-parameter dust model fitting the absolute reddening curve using V-band photometry, the star's absolute magnitude M_V, and the visual extinction A_V derived without knowldege of the trigonometric distance, under the assumption that 50% of the dust mass is in dark dust; see

Full-Model Estimator of A_V (AbsreDgaia):

Code for a full-parameter dust model fitting the absolute reddening curve using V-band photometry, the star's absolute magnitude M_V, and the visual extinction A_V derived from the the trigonometric distance D_{Gaia}; see

- Unification of luminosity and trigonometric (Gaia) distances before (left) and after (right) applying the A_V estimators.

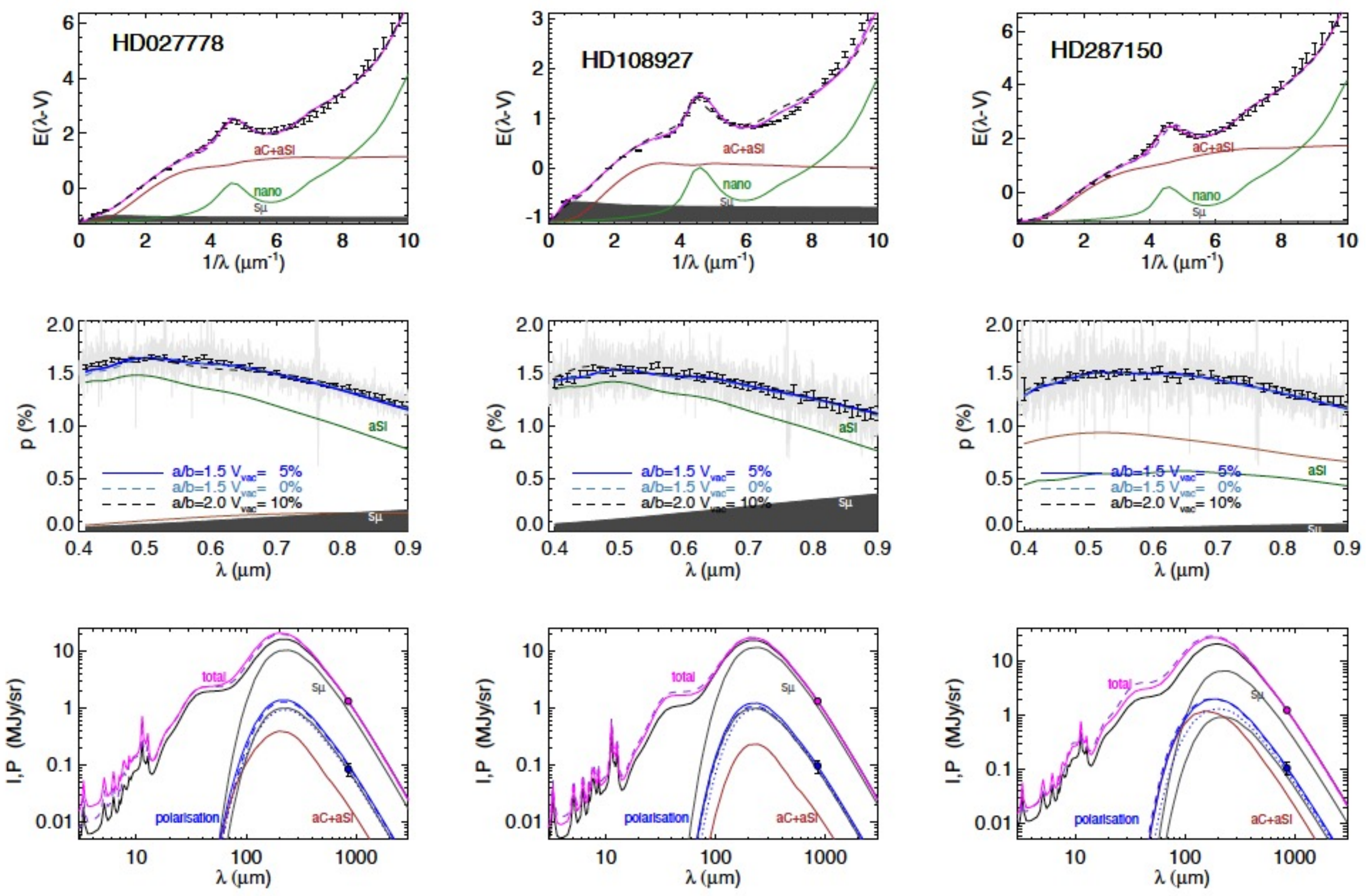

Figure 1: Dust models for HD027778 (left), HD 108927 (middle), and HD287150 (right). For each star we show the reddening curve (top), the FORS polarisation spectrum (middle), and the total (I, magenta) and polarised (P, blue) emission spectrum (bottom). Two best-fit models (dotted and dashed lines) are shown along with a nominal reference model (solid lines). Contributions from nanoparticles (green), amorphous grains (brown), and submicrometre grains (grey) are visualised consistently in both extinction and polarised emission.

Results:

- Models with axial ratio a/b = 1.5 and porosities of 5% for both the amorphous and submicrometre grains successfully fit the three LIPS sightlines with Planck data, and 24 additional sightlines that have high-quality reddening curves and LIPS polarization spectra.
- A single-cloud model generally provides fits within the 1-σ uncertainty.
- Submicrometre grains contribute most notably to the near-infrared extinction, and in most cases their contribution to the FORS optical polarisation is small.
- Submicrometre grains contribute about one-third of the total extinction and represent approximately half of the total dust mass. Significant variations in dust abundances occur from cloud-to-cloud.

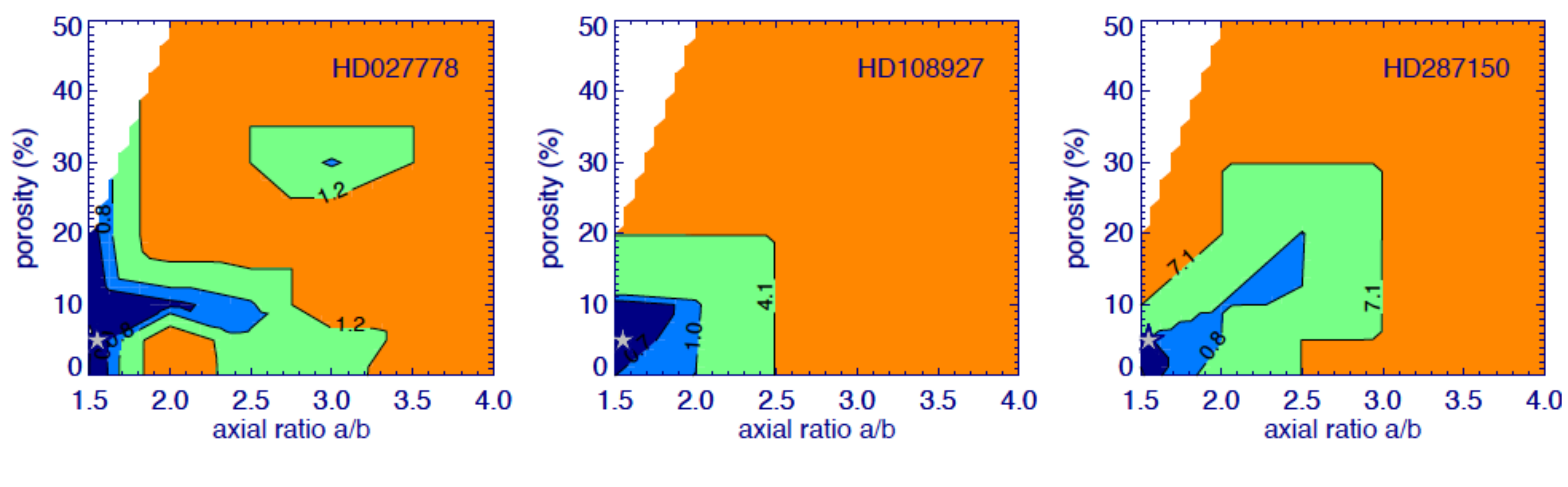

Figure 2: Total goodness-of-fit (χ^2), normalised to the nominalreference model, as a function of axial ratio a/b and porosity of the amorphous grains, for HD 027778, HD 108927, and HD 287150. Regions with acceptable fits are shown in blue and regions with poor fits are shown in orange.

Dark Dust model (Siebenmorgen 2023) : The dataset is used to constrain the properties of grains in the diffuse ISM using a three-component dust model, consisting of nanoparticles, amorphous grains, and submicrometre-sized "Dark Dust". Nanoparticles are responsible for the far-UV rise in the reddening curve, the 2175 Å bump, and the mid-infrared emission bands. Amorphous grains produce nearly grey extinction in the far-UV and an almost linear decline toward longer wavelengths, and they dominate the far-IR emission. Submicrometre-sized grains contribute grey extinction in the optical, a linear decline in the near-IR, and the submillimetre emission. The optical polarisation is dominated by amorphous grains, while the 850µm emission polarisation is dominated by the submicrometre grains.

Dust alignment

The polarization of starlight by dust extinction (Hall 1949, Hiltner 1949) and of polarized thermal dust emission (Hildebrand 1988) show that interstellar dust grains are non-spherical and aligned with respect to the interstellar magnetic field. This is the result of a rotating grain's axis of maximum inertia **a** aligning with its angular momentum **J** (*internal* alignment) while J aligns with the magnetic field line direction B (*external* alignment).

Internal alignment is generally agreed to be driven by the Barnett effect Purcell1979). Theories suggested to explain external alignment include paramagnetic relaxation Davis-Greenstein (1951) and the torque exerted by an anisotropic radiation field on a helical grain due to the differential scattering/absorption of left- and right-handed circular polarization radiative torque (RAT theory, Dolginov & Mitrofanov 1976, Draine & Weingartner 1996).

Following the development of an analytical model for RAT (Lazarian 2007), and due to its good qualitative agreement with polarimetric observations (e.g. Andersson+2015), interest in RATs has increased significantly in the last two decades. The high polarization ceiling observed in dust thermal emission ($p_{850\,\mu m} \sim$ 20%, Planck Collaboration 2015) requires that dust grains be more efficiently aligned than either the DG effect or the RAT alignment in its original form can account for. A solution found by Hoang & Lazarian 2016) is to consider grains with iron inclusions, resulting in increased grain magnetic susceptibility, and therefore alignment: this is the magnetically enhanced RAT, or MRAT, theory. Note that, while DG torques are also enhanced by iron inclusions, they are typically significantly weaker than MRAT torques.