Dust & Polarization in the Interstellar Medium

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Polarized Dust in the ISM

• Polarization: optical through mm wavelengths
  – Why is light polarized? → dust grains are aligned
  – Why, Where, and How are grains aligned with $B$-field?
• Polarization spectra observations (among others)
  – optical extinction (near-UV thru near-IR) in diffuse ISM
  – FIR/MM emission in dense clouds
• "Unified" models to explain polarized emission & absorption
• Extension to …
  – emission from Dark clouds and the diffuse ISM
  – Longer wavelengths: $\lambda \rightarrow 3$ cm, $\nu \rightarrow 10$ GHz
Where is Dust/Light Polarized?

Colored vectors = FIR/SMM (e.g., Stephens, et al. 2011)
Black = optical (Heiles 2000)

inferred $B$-field direction

NGC 6334
(Novak et al. 2009)

$A_V \sim 30$

1000 AU

NGC1333
SMA (Girart et al. 2006)

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Where is dust aligned?

- Polarization observed in both diffuse ($A_V < 5$) and dense ($A_V > 10$) regions of ISM

- Is polarization tracing $B$-fields in all these environments? – need consistent alignment model
Ferromagnetic alignment?

- Alignment easily disrupted by collisions
- Insufficient Fe in dust
- $B$-field too weak (< mG)
  - $B_{MW} \sim \text{few } \mu\text{G}$
Paramagnetic Grain Alignment

**Goal:** \( \tau(\text{align}) < \tau(\text{collision}) \approx 10^{13} \text{ sec.} \)

\[ \vec{B} - \text{Magnetic Field direction} \]
\[ \vec{J} - \text{Angular momentum (spin axis)} \]
\[ \vec{a} - \text{grain's largest inertial moment} \]

**Step 1: Internal Alignment**
- internal relaxation / dissipation, via (nuclear) Barnett-effect

**Step 2: Angular Momentum alignment**
- paramag. dissipation, suprathermal rot'n \& H\_2 torques?
- radiative torques

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Davis & Greenstein 1951
Jones & Spitzer 1967
Purcell 1979
Lazarian \& Draine 1999
Hoang \& Lazarian 2008
Radiative Alignment Torques (RAT)

- $\vec{F}$ is the alignment torque (\perp to $\vec{J}$)
- $\vec{H}$ is the spin-up torque (\parallel to $\vec{J}$)

An asymmetrical grain has different right- and left-handed helicity components and therefore couples differently to right- and left-handed circularly polarized radiation components

- What are values $\xi_0$ and $J_0$ such that $\langle \vec{F} \rangle = \langle \vec{H} \rangle = 0$, and $d\langle \vec{F} \rangle / d\xi < 0$?

- Exact answer is a function of things like: radiation field, grain size, wavelength, $\Psi$, ...

\[ \xi_0 \approx 0 \text{ or } \pi \]
Tests of Alignment Theories

• Predictions of the Radiative Torque Model:
  – Alignment efficient up to $A_V \sim 10$, necessary for dense regions
    • compared to H$_2$ torques which drop at lower $A_V$ (i.e., no more free-H)
    • difference in $T_{\text{gas}}$ and $T_{\text{dust}}$ not necessary
  – Increased grain alignment efficiency with exposure to photons
    • Drop in polarization with opacity; "polarization holes"
    • Drop in polarization with distance from radiation source
  – Larger grains are better aligned than small grains
    • shift in polarization spectrum
  – Polarization dependent on angle between radiation direction and magnetic-field
Near-optical wavelengths ($\lambda \sim a$)

- large grains (traced by NIR) better aligned than small grains (traced by UV); e.g. Kim & Martin 1995

FIR–MM wavelengths ($\lambda \gg a$)

- multiple domains of grain temperature and polarization/alignment; Hildebrand et al. 1999
- most recent: Vaillancourt & Matthews 2012
Simplified Cloud Model

$n(a) \sim a^{-3.5}$

$\langle a \rangle \sim \lambda_{\text{max}}$

Temperature

Size Distribution

polarization

grain size

$A_V$
Simplified Cloud Model - NIR

Temperature

Size Distribution

\( n(a) \sim a^{-3.5} \)

\( \langle a \rangle \sim \lambda_{\text{max}} \)

\( \langle a \rangle \)

\( A_V \)

\( \lambda_{\text{max}} \)

In near-visible \( \Rightarrow \) correlation between \( \lambda_{\text{max}} \) and \( A_V \)

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Simplified Cloud Model - NIR

In near-visible $\Rightarrow$ anti-correlation between $\lambda_{\text{max}}$ and Temperature

\[ n(a) \sim a^{-3.5} \]

\[ \langle a \rangle \sim \lambda_{\text{max}} \]

\[ \lambda_{\text{max}} \text{ vs. Temperature} \]

(Andersson & Potter 2010)
Polarized Emission vs. Wavelength

(350 µm grayscale/contours)

Dotson et al. 2000, 2010; Chrysostomou 2002
Comparing **Hertz** & **SCUBA**

**Hertz @ CSO 350 \( \mu \text{m} \)  **SCUBA-pol @ JCMT 850 \( \mu \text{m} \)

**Data Cuts:** \( P > 3\sigma_p \) and \( |\phi(850) - \phi(350)| < 10^\circ \)

**All 14 Objects:** Median \( P \)-ratio = 1.7 ± 0.6

Vaillancourt & Matthews 2012
Comparing Hertz & SCUBA

Hertz @ CSO 350 µm  SCUBA-pol @ JCMT 850 µm


Polarization Ratio
P(850) / P(350)

Data Cuts: $P > 3\sigma_p$ and $|\phi(850) - \phi(350)| < 10^\circ$

All 14 Objects: Median $P$-ratio = $1.7 \pm 0.6$
Dust emission from
• A single grain species at
• A single temperature
(Hildebrand et al. 1999)

Does not match Observations!
Dust emission from
- A single grain species at
- A single temperature  
  (Hildebrand et al. 1999)

Dust emission from
- multiple grain species
- multiple temperatures or emissivities  
  (Hildebrand et al. 1999)

\[ P_\nu F_\nu = \sum_i p_i \nu^{\beta_i} B_\nu(T_i) \]
Grain alignment model in *starless* clouds:
- Nearly all grains exposed to same I.S. radiation field
- Large grains are more efficiently aligned
- Large grains cool more efficiently
  \[\Rightarrow\] Colder grains better aligned than warm grains

Bethell et al. 2007 (RAT)

Draine & Fraisse 2009 (empirical ext. & pol.)

- only SiO pol.
- SiO + C
Homogenous Cloud: $T_A > T_B$, $p_A < p_B$
Homogenous Cloud: $T_A > T_B$, $p_A < p_B$
Simplified Cloud Model – FIR

Homogenous Cloud: $T_A > T_B$, $p_A < p_B$

RAT model, Cherpunov & Lazarian, priv. comm.
• Observed cloud SEDs indicate wide dust temperature distribution
• Polarization $\lambda$-minimum constrains SED models
  – Function of components’ temperature $T$, and spectral index $\beta$
  – Independent of relative & total column densities
Correlation between Polarization and stellar locations
- use $P$-spectrum (ratio) to eliminate change in spatial environment
- Existing SMM observations (20 arcsec) insufficient to resolve stars
- SHARP (10” at 350 µm) or SCUBA-2 (7” @ 450 µm) may resolve stars
- SOFIA (5” - 10” @ 50 - 100 µm), more sensitive to warm dust near stars
• All grains likely exposed to same environment

• Finkbeiner, Davis, & Schlegel (FDS99) — high latitude dust
  – $T = 9.5\, \text{K}, \beta = 1.7$ (silicate ?)
  – $T = 16\, \text{K}, \beta = 2.7$ (graphite ?)

• If silicate is polarized and graphite unpolarized then $T_C > T_{Si}$, $p_C < p_{Si}$, $\beta_C > \beta_{Si}$

• Predictions at $\lambda > 1\, \text{mm}$
  (Hildebrand & Kirby 2004; Bethell et al. 2007; Draine & Fraisse 2009)
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Millimeter Polarimetry

BICEP Polarimetry at 96, 150, 210 GHz (3.1, 2.0, 1.4 mm) [Bierman et al. 2011]

• High-frequency data is dominated by dust and...
BICEP Polarimetry at 96, 150, 210 GHz (3.1, 2.0, 1.4 mm) [Bierman et al. 2011]

- High-frequency data is dominated by dust and
- Polarization is approx. constant with frequency
The Future of Dust Polarimetry

Need new instruments which
- Cover wide spectral range
- Better sampled polarization & total intensity SEDs
- Increases spatial resolution & sensitivity
- New environments, other than dense clouds

Instruments like...
- HAWC / SOFIA
- SHARP / CSO
- SCUBA-2 / JCMT
- CCAT
- ALMA
- Planck

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The Future of Dust Polarimetry

(e.g., Dowell et al. 2010)
The Future of Dust Polarimetry

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Polarized Dust in the ISM

- Optical dust-extinction and FIR dust-emission is polarized, grains are aligned with $B$-fields
- Both optical and FIR polarization-spectra are consistent with multiple domains of grain size, temperature, and polarization
- Radiative Torques are consistent with polarization observations in both the optical/NIR (extincted starlight polarization) and FIR/MM (polarized emission)
- Future Tests
  - Better sampling of intensity & FIR-MM polarization spectrum
  - Observations in diffuse ISM; different environment from Galactic clouds
  - Look for correlation with stellar locations to test alignment models
  - Future instruments: HAWC/SOFIA, SCUBA-2, Planck, ALMA