Dust Properties in our Galaxy
Polarization and Microwave Emission

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Cosmic Cycle of Dust and Gas, Quy Nhon, July 8-14, 2018
Golden Age of Dust Polarimetry: Unveiling the Role of Magnetic Fields in Star Formation

Planck Collaboration

B-field in filament

Chapman et al.

NGC 1333 IRAS 4A
SMA

Girart et al. 2006

ALMA, Class I YSO

Alves et al. 2018

B-field in small scale?
Golden Age of CMB Polarimetry: Measuring Gravitational Waves with CMB B-Modes

CMB: Cosmic Microwave Background

CMB Polarization by BICEP2

B-mode pattern

The extended CMB polarimetry family

E < 0, E > 0, B < 0, B > 0
Dust Extinction and Emission

- PAHs and Nanoparticles absorb UV photons and reemit in mid-IR
- Big grains absorb starlight and reemit in IR
- Interstellar dust consists silicate and carbonaceous grains
Starlight Polarization and Polarized Emission

Starlight Polarization (1951: Hall, Hilner)

Polarized Emission by Planck

\(\lambda_{\text{max}} \approx 0.55\text{um}\)

\(\frac{\lambda_{\text{max}}}{\lambda}\) far-UV drop

Guillet+ 2017
Polarization of Spectral Features: Silicate and Carbonaceous Dust

Amorphous silicate: e.g., MgFeSiO$_4$

C-H stretch 3.4 µm

Si-O stretch ~10µm feature

Ice feature 3.1 µm

Martin & Whittet 90

Chiar + 2006

Aliphatic hydrocarbons

Aromatic hydrocarbons
First Detection of Polarized PAH Feature

Out-of-plane (C-H) mode: 11.3\micro m

Han, Telesco, Hoang, Pantin, et al. (2017) Using CanariCam/GTC telescope

Theoretical Predictions by Hoang (2017b)
How dust produce polarization?

- Polarization depends on grain alignment degree & grain elongation

\[ P_{\text{ext}} \]

\[ P_{\text{em}} \]

\[ P=0 \quad \text{small } P \quad \text{large } P \]
70-Year History of Grain Alignment Theory

1949: Discovery of starlight polarization (Hall 1949, Hilner 1949)
1949: L Spitzer & Turkey: Ferromagnetic alignment (grains as compass needle)
1951: Davis & Greenstein: Paramagnetic Relaxation. Text book!!!
1951: T. Gold: Mechanic torque alignment based stochastic collisions
1976: Dolginov & Mitrophanov: Radiative torques (RATs) caused by photon angular momentum
1979: E. Purcell: Pinwheel torques+ paramagnetic relaxation
1986: J Mathis: Superparamagnetic relaxation (grains with iron inclusion)
1997: Lazarian & Draine: thermal flipping and trapping
1996-2003: Draine & Weingartner: numerical study of RATs, empirical
2007- present: Lazarian & Hoang, Hoang & Lazarian
Analytical Model of RATs and Era of Quantitative Polarimetry
2016: Hoang & Lazarian: a unified theory of grain alignment
2018: Mechanical torque (MAT) alignment (Hoang, Lazarian, Cho 2018)
Internal and External Alignment

Stage 1: $\omega$ aligned with $J$

- Nutation of $\omega$ around $J$, $\tau_n < 10^{-5}$ s
- $t_{\text{int}} \sim 10^2$ s
- Barnett relaxation
- Inelastic relaxation
- Alignment of $\omega$ with $J$: internal alignment

Stage 2: $J$ gets aligned with $B$

- Precession of $J$ around $B$, $\tau_{\text{Lar}} \sim 10^5$ s
- $\mu$-dipole
- Alignment of $J$ with $B$, $T_{\text{ali}} < 10^{11}$ s
How dust grains interact with B-field?

Paramagnetic grain

Magnetization by external field

Magnetization due to spinning (Barnett effect): more efficient
Paramagnetic Relaxation: Textbook Mechanism is not efficient

Davis & Greenstein (1951)
- Grains are paramagnetic
- Relaxation induces gradual alignment with B-field

Hoang & Lazarian (2016)

\( T_{\text{rot}} / T_{\text{gas}} \approx 6\% \) level
Radiative Torque (RAT) Alignment Mechanism

Lazarian & Hoang (2007ab)
Analytical Model (AMO) of RATs

$k$ is radiation beam direction,
$a_1$ is grain maximum inertia axis, $a_2a_3$ grain principal axes
$N$, normal vector of mirror, lies in $a_1a_2$ mirror plane tilted by angle $\alpha$ with $a_2a_3$

Lazarian & Hoang (2007a) RATs produced by photon momentum on helical grains

RATs produced by photon momentum on helical grains
Analytical Model (AMO) of RATs

RATs from AMO vs. DDSCAT

Suprathermal rotation by RATs

GMC, 10kpc

$A_V=0$

$A_V=5$

$A_V=10$

Lazarian & Hoang 2007a
Hoang & Lazarian 2008
As part of the Federal Wind Energy Program of the Department of Energy, NASA Lewis Research Center conducted tests on the DOE/NASA Mod-O horizontal-axis wind turbine with a one-bladed rotor configuration. The single blade had an overall length of 15.2 m, and used a pitchable tip that spanned 12 percent of the blade radius. The blade was balanced by a counterweight assembly that consisted of a solid steel ellipsoid supported at an outer radius of 4.6 m by a steel spar. The blade and counterweight assembly were mounted to a teetered hub in a downwind configuration.

The objectives of these tests were to obtain data on the performance, loads, and dynamic characteristics of an intermediate-size, one-bladed rotor. These data, measured at a nominal rotor speed of 49 rpm, were compared with corresponding data for a two-bladed rotor at 33 rpm, having the same blade length and airfoil characteristics. The two-bladed rotor was previously operated on the same machine. The one-bladed and two-bladed rotors used common components wherever possible and did not represent optimized rotor designs.

The results of the one-bladed rotor tests showed that this configuration can be operated successfully. There were no significant dynamic loads with this configuration, and the fatigue loads were comparable to those of a two-bladed rotor. A decrease in power output equivalent to a reduction in wind-speed by 1 m/sec occurred with the one-bladed rotor when compared with the aerodynamically similar two-bladed rotor operating at two-thirds of the rotor speed. Analytical methods for predicting the performance and dynamic characteristics of a one-bladed rotor were verified.
RATs can align grains with B-field

\[ \frac{d\vec{J}}{dt} = \text{RATs} - \text{drag} = H \frac{\vec{J}}{J} + F \xi - \frac{\vec{J}}{\tau_{\text{drag}}} \]

\((k,B) = 70\) degree

k parallel to B-field

low-J attractor

high-J attractors

high-J repellor
Super-RATs: grains with iron inclusions can be perfectly aligned

SRAT: no gas randomization

New effect: gas random collisions kick grains out of the low-J attractor

SRAT: with gas randomization

SRAT alignment can be perfect

Hoang and Lazarian (2008, 2016)
Predictions of RAT Alignment

1. Larger grains are more efficiently aligned than small grains
2. Alignment efficiency increases/decreases with increasing/decreasing the radiation intensity
3. Alignment efficiency decreases with the angle of radiation and B-field
4. Grains are aligned with the magnetic field, but can also be aligned with the radiation direction
5. Pinwheel torques (H₂ formation) can enhance grain alignment
6. RAT alignment is perfect for superparamagnetic grains

Review by Lazarian, Andersson, & Hoang 2015 for theory

See ARAA by Andersson et al. for observational tests

RAT theory implemented in public codes (POLARIS code (Reissl & Bauer)
Other Works on RAT Alignment

• Dolginov & Mytrophanov (1976):
  ○ noticed the importance of grain helicity
  ○ calculated RATs for two twisted spheroids

• Draine & Weingartner (1996, 1997) computed RAT for three grain shapes using Discrete Dipole approximation code (DDSCAT)

• Herranen, Markkanen & Muinonen (2018) computed RATs for many shapes. RAT alignment demonstrated numerically
Dust Polarization in Circumstellar Disk

- Very high gas density
- Very large grains (VLGs)

Polarization Mechanisms
1. Grain alignment with magnetic field (LH 2007, HL08, 09ab)
2. Grain alignment with radiation field (LH07, HL08, Tazaki+17)
3. Self-scattering (Kataoka et al.)
Can VLGs be aligned with B-field?

- Paramagnetic grains ($N_{cl}=1$) cannot be aligned with B-field
- Grains with iron inclusions ($N_{cl}>>1$) can be aligned with B-field

$N_{cl} = 10^4 \sim 2$nm Fe nanoparticle

\[ \frac{\tau_{Lar,\text{sup}}}{\tau_{\text{gas}}} \approx 22.2 \times 10^{-3} \frac{n_{10} T_2^{1/2} a_{-5} \Gamma_||}{N_{cl,5} \phi_{sp,-2} B_3} \]

\[ a_1 < 436 \frac{N_{cl,5} \phi_{sp,-2}}{n_{10} T_2^{1/2} B_3 \Gamma_||} \mu m \]

- Mid-plane Alignment:
  - $a_1 \sim 0.005 \mu m$ for $N_{cl} \sim 1$
  - $a_1 \sim 0.5 \mu m$ for $N_{cl} \sim 100$
  - $a_1 \sim 50 \mu m$ for $N_{cl} \sim 10^4$

*Hoang & Lazarian (2016)*
Can VLGs be aligned with k-field?

Alignment with illumination direction: $k$ - RAT align

1. VLGs can be aligned with $k$-field, but not $B$-field
2. Small grains with iron inclusions can be aligned with $B$-field

Lazarian & Hoang (2007a)
Hoang & Lazarian (2014, 2016)

Modified from Tazaki et al. 2017
ALMA Polarization from HL Tau

Theory

Radiative Alignment

Tazaki et al. 2017

Observations

Stephens+17

Self-scattering

Kataoka et al. 2017
ALMA Polarization from Circumbinary Disk

Detection of Poloidal Fields?

- Polarization pattern does not change with wavelength

See Sadavoy+ 2018, Hull+2018, Girat+2018
Kogut et al. found emission excess at 31 GHz from COBE data.

Leitch et al. found emission excess at 14.5 & 31GHz (AME intro).
AME Origin

- 1998 Draine and Lazarian: spinning dust emission

- 1999 Draine and Lazarian: magnetic dipole emission from iron nanoparticles
Selected AME regions discovered by Planck 2011

Planck Collaboration 2011, A20
Spinning dust provides a great fit to AME from Planck

Perseus Cloud
Planck Collaboration+2011

spinning dust
thermal dust
free-free
98 clouds with AME discovered by Planck 2013
Theory of Spinning Dust Emission

Emissivity integrated over size distribution:

$$\frac{j_\nu}{n_H} = \frac{1}{4\pi a_{\text{min}}^{a_{\text{max}}}} \int da \frac{1}{n_H} \frac{dn}{da} 4\pi \omega^2 f_\omega 2\pi P_{\text{ed}}(\omega)$$
spinning PAH (Planck collaboration 2011)

spinning iron nanoparticle (Hoang & Lazarian 2016)

spinning nanosilicates (Hoang, Vinh, & Lan 2016)
Spinning dust becomes an accepted CMB foreground component
# Key Developments of Spinning Dust Theory

<table>
<thead>
<tr>
<th>Development</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>First proposal for electric dipole radiation from quantum suppressed dust</td>
<td>Erickson (1957)</td>
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<tr>
<td>First full treatment of spinning dust grain theory</td>
<td>Draine and Lazarian (1998b)</td>
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<td>Quantum suppression of dissipation and alignment</td>
<td>Lazarian and Draine (2000)</td>
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<tr>
<td>Factor of two correction in IR damping coefficient</td>
<td>Ali-Haïmoud et al. (2009)</td>
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<tr>
<td>Fokker-Planck treatment of high-$\omega$ tail</td>
<td>Ali-Haïmoud et al. (2009)</td>
</tr>
<tr>
<td>Quantum mechanical treatment of long-wave radiation</td>
<td>Ysard and Verstraete (2010)</td>
</tr>
<tr>
<td>Rotation around non-principal axis</td>
<td>Hoang et al. (2010); Silsbee</td>
</tr>
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<td>Transient spin-up events</td>
<td>Hoang et al. (2010)</td>
</tr>
<tr>
<td>Effect of tri-axiality on rotational spectrum</td>
<td>Hoang et al. (2011)</td>
</tr>
<tr>
<td>Effects of transient heating on emission from tri-axiality</td>
<td>Hoang et al. (2011)</td>
</tr>
<tr>
<td>Magnetic dipole radiation from ferromagnetic dust</td>
<td>Hoang and Lazarian (2016b)</td>
</tr>
<tr>
<td>Improved treatment of quantum suppression</td>
<td>Draine and Hensley (2016)</td>
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**AME from nanosilicates:** Hoang + (2016), Hensley & Draine (2017)

**AME polarization:** Hoang + (2013), Hoang & Lazarian (2016a, 2017)
Spinning dust as a tracer of nanoparticles

Why nanoparticles?

- Nanoparticles play important roles in disks (e.g., MRI activity, ambipolar diffusion)

Advantages over mid-IR

- Can trace nanoparticles in any regions (cf. Mid-IR)
Spinning Dust Emission from Disks

- Spinning dust dominates over thermal dust at freq < 70 GHz

Posted on March 29, ArXiv: 1803.11028
Diamond Dancing in Circumstellar Disk?

- AME might not originate from nanodiamond
- Spinning PAHs/Nanosilicates cannot be ruled out
Microwave Emission from Disk Cavity

Dong et al. 2018, arXiv:

Casassus et al. 2018, arXiv:
Summary

- Dust polarimetry is a powerful technique to study magnetic fields, dust properties, and important for cosmic inflation.
- **Interstellar Polarization**: Radiative torque (RAT) alignment is main mechanism, tested with numerous observations.
- **Disk Polarization**: Multiple mechanisms exist. Evidence of Radiative Alignment and Self-scattering. How to distinguish them? Circular polarization? Multiwavelength observations?
- **Polarized PAH emission**: first detection, consistent with theoretical predictions by PAH alignment with B-field
- **Microwave emission**: spinning dust from nanoparticles. Become a tracer of nanoparticles, huge potential with ngVLA, SKA, and ALMA Band 1
- Future: how to use quantitative polarimetry to probe dust properties (iron inclusions and magnetic properties)?
Welcome to Cosmic Dust and Magnetism 2018

Scientific Rationale and Scope

Dust and magnetic fields are ubiquitous in the context of star and planet formation, while important for astrophysical phenomena, including synchrotron emission. The alignment of dust and magnetic fields, resulting in dust polarization, is an important method to trace magnetic fields, but great care is needed to disentangle dust polarization from other mechanisms that can produce similarly polarized emissions. Therefore, accurate modeling of dust and magnetic fields is necessary to understand how the universe works. The aim of this workshop is to bring together experts in dust astrophysics and magnetism to address the following important aspects:

1. Dust Properties and Dust Evolution of planetesimals
2. Physics of Dust Polarization in stellar wind tests
3. What is the role of magnetic fields in planet formation?
4. What can we learn from mm-wave era: Magnetic fields or Grain Growth?
5. Alternative ways to trace magnetic fields?
6. Related important issues: turbulent fields
7. What dust astrophysics and Galactic foreground for CMB B-field

Confirmed Invited Speakers:

- Andersson, B-G (NRAO)
- Balsara, Dinshaw (NASA JPL)
- Boulanger, Francois (CNRS/LAMS)
- Burkhardt, Blakeslee (NASA GSRB)
- Clemens, Dan (Boston College)
- Draine, Bruce (Princeton University)
- Federrath, Christoph (University of California, Santa Barbara)
- Fissel, Laura (NRAO)
- Girart, Josep M. (CSIC)
- Guillem, Vincent (IAS-EPFL)
- Hensley, Brandon (NASA GSRB)
- Hirashita, Hiroyuki (University of Tokyo)
- Hoang, Thiem (KASI)
- Houde, Martin (UW-AMOS)
- Hull, Chat (NAOJ, CTIO)
- Kataoka, Akimasa (IPMU)
- Kwok, Sun (University of Hong Kong)
Theoretical predictions vs. Observations

Simulations by Dickinson’s

Dickinson, Hoang, et. al (2017)

ratio by more than 1σ. For sensitive CMB experiments, omitting in the foreground modelling a 1% polarized spinning dust component may induce a non-negligible bias in the estimated tensor-to-scalar ratio.