Grain Alignment Theory & New Physics of Dust Grains

Thiem Hoang (KASI & UST)

Collaborators: A. Lazarian (UW-Madison), B-G Andersson (NASA), Jungyeon Cho (Chungnam), D. Whittet (Rochester)

Postdocs: Tram Le, Hyeseung Lee

ALMA Polarimetry, March 26-29, 2019, NAOJ, Mitaka
What I will talk about:

1. Review of Grain Alignment Theory
2. The fastest mechanism to destroy large grains into small grains

Hoang, Tram, Lee & Ahn (2019), Nature Astronomy, in press
3. The most efficient mechanism to release COMs/water from icy grain mantles

Hoang & Tram (2019b)
Grain Alignment Theory for Interstellar Grains

- Low-moderate gas density ($n < 10^5 \text{ cm}^{-3}$)
- Small grains ($a < 1$ micron)

- Image shows a grain with estimated size of approximately 0.2 microns.
1949: Discovery of Starlight Polarization

ISM as a polarizer

Observations of the Polarized Light From Stars

John S. Hall
U. S. Naval Observatory, Washington, D. C.

PHOTOMETRIC OBSERVATIONS of the light from stars were made during the period November 1946 to January 1948 with the 26-inch reflector at Washington. Observations were made on 223 stars, selected from a list of 300 stars in the vicinity of the Sun. The aim of the experiment was to determine the polarization of light from stars, and to see if the percentage of polarization could be related to the distance of the star from the Sun.

The results of the observations are shown in the accompanying graph. The percentage of polarization is plotted against the distance of the star from the Sun. The distance is expressed in parsecs, and the percentage of polarization is given in percent.

The graph shows that the percentage of polarization decreases with increasing distance from the Sun. This is in agreement with the theory that the polarization of light from stars is due to the scattering of light by interstellar dust particles.

Furthermore, the percentage of polarization is found to be related to the brightness of the star. The brighter stars have a higher percentage of polarization.

This work was supported by the National Science Foundation.

[Graph showing the relationship between distance from the Sun and percentage of polarization, with a note that the graph is intended to be a reproduction of the original data.]

Dr. Hall, working with Dr. Hall, was able to use a photographic method to determine the polarization of light from stars. The results of this work are shown in the accompanying photograph. The photograph shows a star field with the polarization of light from each star indicated by a arrow. The arrows point in the direction of the polarization, and the length of the arrow indicates the percentage of polarization.

The graph shows that the percentage of polarization increases with increasing distance from the Sun. This is in agreement with the theory that the polarization of light from stars is due to the scattering of light by interstellar dust particles.

Furthermore, the percentage of polarization is found to be related to the brightness of the star. The brighter stars have a higher percentage of polarization.

This work was supported by the National Science Foundation.

[Photograph showing a star field with polarization arrows, with a note that the photograph is intended to be a reproduction of the original data.]
Interstellar Polarization, Galactic Magnetic Fields, and Ferromagnetism

Lyman Spitzer, Jr., and John W. Tukey

Princeton University

OBSERVATIONS by W. A. Hiltner (5, 6) and J. S. Hall (4) indicate that starlight becomes plane polarized in its passage through interstellar space. The effect increases with increasing distance, and according to Hall's data amounts to about 5 percent (= $e^{0.05}$) difference in intensity between the two plane-polarized components for a star whose color excess is 0.50 magnitude. Since the color excess is known to be about one-ninth the total absorption (which thus amounts to $(2.512)^{-4.8} = e^{-4.1}$ for such a star), the absorption must vary by somewhat more than one percent with the plane of polarization.

Such polarizing absorption would exist if needle-shaped particles, of dimensions comparable with a wavelength of visible light, were present in interstellar space, and were oriented by some force. The ratio of the scattering cross sections of such needles for the two planes of polarization would be appreciable; according to the theory by R. Gans (3), for a small prolate spheroid with a length twice its diameter, this ratio is 2.74 if the refractive index in the spheroid equals 2.5. Thus a relatively small number of needles could produce the observed effect.

Two difficulties seem to stand in the way of this explanation: the origin of the needles and their orientation. If we accept as a working hypothesis: (1) the existence of small ferromagnetic particles, which, existing as individual domains, are intensely magnetic; and (2) the existence of magnetic fields in interstellar space with systematic components as great as $10^{-5}$ gauss; then these difficulties disappear. The first of these suppositions appears reasonable from an exten-
How dust grains produce polarization?

- Polarization depends on grain alignment degree & grain elongation

P=0, small P, large P
Alignment Properties from Observed Polarization

1. Small grains are weakly aligned
2. Big grains are efficiently aligned
3. Silicate grains are efficiently aligned and non-spherical.

4. Carbonaceous grains are weakly aligned or spherical.

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

Aliphatic hydrocarbons
History of Grain Alignment Theory

- **1949, 1951**: paramagnetic relaxation
- **1979**: spin-up by pinwheel torques
- **1999**: thermal flipping
- **1976 - 1996 - 2007–**: RAdiative Torque (RAT) alignment

- Dolginov & Mitraphanov (1976)
- Draine & Weingartner (96, 97)
- Lazarian & Hoang (2007)
- Hoang & Lazarian (2016): unified theory

*Contributors:* Davis-Greenstein, E Purcell, L Spitzer
Internal and External Alignment

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

- Time $t_{\text{int}} \approx 10^2 \text{ s}$
- Barnett relaxation
- Inelastic relaxation
- Alignment of $\omega$ with $J$: internal alignment

- Nutation of $\omega$ around $J$, $\tau_n < 10^{-5} \text{ s}$

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

- $\mu$-dipole
- Precession of $J$ around $B$, $\tau_{\text{Lar}} \approx 10^5 \text{ s}$

- Alignment of $J$ with $B$, $\tau_{\text{ali}} < 10^{11} \text{ s}$
How dust grains interact with B-field?

Paramagnetic grain

Magnetization by external field

Magnetization due to spinning (Barnett effect): more efficient
Grain gets magnetized due to spinning
Barnett effect (inverse of Einstein de-Hass effect)
Davis-Greenstein alignment inefficient due to slow rotation

\[ \frac{T_{\text{rot}}}{T_{\text{gas}}} \approx 0.4 \]

\[ \sim 6\% \text{ level} \]

Hoang & Lazarian (2016)
Radiative Torques of Irregular Grains

- 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)

- Grains of 3 shapes can be aligned by RATs
- But no predictive power due to unknown shape of grains
- Need an analytical model for predictions
Experiment Test of Spin-up by RATs

Abbas et al. (2004)

- Rotation rate ~ Radiation Intensity
- Stronger radiation, faster rotation
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
Analytical Model (AMO) of RATs

RATs from AMO vs. DDSCAT

Lazarian & Hoang 2007a
Hoang & Lazarian 2008
Herranen, Lazaro
• good agreement
• little dependence compositions

RATs of Many Irregular Grains Agree with AMO
SUMMARY

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.
RAT Alignment: Equation of Motion

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

\((k, B) = 70 \text{ degree}\)

Light beam

Magnetic field

\(\xi\)

\(k\) parallel to \(B\)-field

low-J attractor

high-J attractors

paramagnetic grain
Interstellar dust grains may contain iron nanoparticles, as revealed by in-situ data.
Superpara RAT (SRAT) alignment: grains with iron inclusions

- Gas random collisions kick grains out of low-J attractor
- 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 is implemented in POLARIS code (Reissl & Bauer)
Observations: RAT alignment decreases with starlight radiation intensity

Alves et al. 2014

ISM photon

Whittet et al., incl Hoang (2008)

starless cores
Jones + 2015

$\sim 1/Av$
Observations: RAT alignment increases with increasing radiation intensity

Maury et al. 2018: Strong polarization in outflow cavity walls due to enhanced radiation from stars enabled by cavity
Grain Alignment in Disks

- High gas density \( (n>10^9 \text{ cm}^{-3}) \)
- Very large grains \( (a>10 \text{ micron}) \)

Three Mechanisms

1. Grain alignment by radiative torques (magnetic field and radiation direction)
2. Grain alignment by mechanical torques (magnetic field and gas flow)
3. Self-scattering
Can VLGs be aligned with B-field?

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

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 incl can be aligned with B-field

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

Modified from Tazaki et al. 2017
Polarization by Radiative Alignment

Azimuthal Polarization

Face-on View

Edge-on View
ALMA Polarization from HL Tau disk

**Model**

Radiative Alignment

Tazaki et al. 2017

Self-scattering

Kataoka et al. 2017

**Observations**

Kataoka al. 2017
2. Discovery of a fastest mechanism to destroy large grains and form nanoparticles

Hoang, Tram, Lee & Ahn (2019), Nature Astronomy, in press

Supernova spin-up by radiative torques disruption by centrifugal force
Why Dust around SNe Ia is Unusual?

Anomalous $R_V<2$ ($R_V=3.1$ for Milky Way)

Properties of interstellar dust responsible for extinction laws with unusually low total-to-selective extinction ratios of $R_V=1 - 2$

Takaya Nozawa

National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

Article Info

Article history:
Received 16 December 2015
Accepted 18 August 2016
Available online 21 August 2016

Abstract

It is well known that the extinction properties along lines of sight to Type Ia supernovae (SNe Ia) are described by steep extinction curves with unusually low total-to-selective extinction ratios of $R_V=1.0 - 2.0$. In order to reveal the properties of interstellar dust that causes such peculiar extinction laws, we perform the fitting calculations to the measured extinction curves by applying a two-component model and dust SNe II-P are good standardizable candles, almost comparable to SNe Ia. We derive a tight Hubble diagram with a dispersion of 10% in distance, using the simple correlation between luminosity and photospheric velocity introduced by Hamuy and Pinto. We show that the descendant method of Nugent et al. can be further simplified and that the correction for dust extinction has low statistical impact. We find that our SN sample favors, on average, a very steep dust law with total to selective extinction $R_V<2$. Such an extinction law has been recently inferred for many SNe Ia. Our results indicate that a distance measurement can be obtained with a single spectrum of a SN II-P during the plateau phase combined with sparse photometric measurements.

Key words: cosmology: observations — distance scale — dust, extinction — supernovae: general

Online-only material: color figures
Why dust around SNe Ia is unusual?

$R_V \sim$ average dust grain size

$R_V \sim 3.1$, Average Milky Way

$R_V = 1.7$

Average SNe Ia

Burns+2014
Why Dust around SNe is dominated by nanoparticles?

Grain size distribution inferred from Hoang T. (2017)

Patat+2015

polarization curves

Standard

unusual

a<0.07um

nanoparticle dominance
What is the origin of NIR-MIR (1-5um) emission excess in HII regions?

Relano +2013, M33
Why abundance of small grains increase toward center of HII regions?

- Thermal sputtering rapidly destroy small grains near the center
- Small grains must be reproduced by some mechanism

NGC 3603
$L_{bol} = 10^7 L_{sun}$

Lebouteiller+2007
Rotational Disruption by Radiative Torques by SNe Flash

- RATD can destroy large grains within 20 days
- Radiation rapidly modifies dust properties
RATD produce nanoparticles around SNe

(b) SNe Ia
$T=15000\ \text{K}$
$S_{\text{max}}=10^3\ \text{erg cm}^{-3}$

<table>
<thead>
<tr>
<th>Mechanisms</th>
<th>Timescales (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATD</td>
<td>$1.0a_{-5}^{-0.7}U_6^{-1}S_{\text{max,9}}^{1/2}$</td>
</tr>
<tr>
<td>Thermal sputtering</td>
<td>$9.8 \times 10^3a_{-5}n_1^{-1}T_6^{-1/2}(0.1/Y_{sp})$</td>
</tr>
<tr>
<td>Non-thermal sputtering</td>
<td>$5.7 \times 10^3\rho a_{-5}n_1^{-1}v_{\text{drift,3}}^{-1}(0.1/Y_{sp})$</td>
</tr>
<tr>
<td>Grain-grain collision</td>
<td>$7.6 \times 10^4\rho a_{-5}n_1^{-1}v_{\text{drift,3}}^{-1}$</td>
</tr>
</tbody>
</table>
3. Discovery of a new, efficient mechanism to release COMs from icy grain mantles
How Can Complex Molecules Evaporate from Ice Mantles at Low Temperatures?

- Sublimation requires high temperatures ($T > 100$ K)
- Observations of COMs from cold regions ($T < 100$ K)
How Can Complex Molecules Evaporate from Ice Mantles at Low Temperatures?

Hoang & Tram (2019b)
Rotational Desorption of Grain Mantles and Rapid Evaporation of COMs

- Stellar radiation
- Transient evaporation from very small fragment
- Enhanced sublimation from small fragment
- Rotational desorption

Grain core
\( a_c = 0.1 \mu m \)

\[ \begin{align*}
&\text{PAHs, CH}_2\text{OH, H}_2\text{O, CH}_3\text{CHO, CH}_3\text{CHO, H}_2\text{O} \\
&\text{NH}_2, \text{NH}_3, \text{HCOOCH}_3, \text{H}_2\text{O, \ldots}
\end{align*} \]
Breaking ice mantles into smaller fragments increases evaporation rate of COMs by 1000 times.

Small ice fragments can evaporate at the same rate as large mantle at $T \sim 40K$ lower.
Rotational desorption dominates over classical thermal sublimation in hot cores.
Summary and Discussion

- Grain alignment is a longstanding question in astrophysics.
- Radiative torque (RAT) alignment appears to be a main mechanism, tested with numerous observations.
- Mechanical torques can be important in some environments with supersonic gas flow: shocks, radiation pressure.
- Radiative torques not only controls grain alignment but also control grain properties via Radiative Torque Disruption (RATD):
  - Unusual dust properties in SNe, NIR-MIR excess in HII regions
  - Upper cutoff of grain size distribution, internal structures
- Radiative torques can induce desorption of COMs at low temperatures below thermal evaporation.
- A synergic study of dust emission, dust polarization, and astrochemistry.
Disruption of Large Grains and COM desorption near Protostars
RATD can destroy large grains around SNe, increasing small grains.
Mechanical Torque (MAT) Alignment

A Helical Grain--AMO

Lazarian & Hoang 2007b, Hoang et al. 2018
Where is MAT alignment important?

- MAT efficiency varies greatly with the grain shape
- MAT can also align along the B-field and gas flow direction
- Supersonic neutral drift in C-shocks

- Drifting due to grain acceleration by MHD turbulence
- Drifting due to radiation pressure acceleration of grains
- Infalling gas in circumstellar disks