Galactic Foreground in Planck Era and Beyond: Emission and Polarization from Interstellar Dust

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Outline

• Introduction to Foreground and Motivation
• New Emissions of Galactic Foreground:
  – Spinning Dust Emission
  – Magnetic Dust Emission
• Polarization of Galactic Foreground:
  – Predictive Model of Grain Alignment
  – Modeling Polarization vs. Observations
  – Inversion Problem
• Summary
Cosmic Microwave Background (CMB)

Isotropy of the Cosmic Microwave Background

night sky at 1 cm

T = 2.7 K

COBE
Precision Cosmology

LAMBDA

K band (23 GHz)

cleaning

Understanding

Galactic Foregrounds

WMAP: Wilkinson Microwave Anisotropy Probe

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^2 \Omega_b h^2$</td>
<td>2.230$^{+0.071}_{-0.070}$</td>
</tr>
<tr>
<td>$\Delta^2_R(k = 0.002/\text{Mpc})$</td>
<td>$(24.1 \pm 1.3) \times 10^{-10}$</td>
</tr>
<tr>
<td>$h$</td>
<td>$0.710 \pm 0.026$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$71.0 \pm 2.6 \text{ km/s/Mpc}$</td>
</tr>
<tr>
<td>$n_s(0.002)$</td>
<td>$0.948^{+0.016}_{-0.015}$</td>
</tr>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02230^{+0.00071}_{-0.00070}$</td>
</tr>
<tr>
<td>$\Omega_{\Lambda}$</td>
<td>$0.735 \pm 0.030$</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.265 \pm 0.030$</td>
</tr>
<tr>
<td>$\Omega_{\text{m}h^2}$</td>
<td>$0.1320^{+0.0063}_{-0.0064}$</td>
</tr>
</tbody>
</table>

Spergel et al. 2003
1996: Discovery of anomalous emission by COBE

- Kogut et al. (1996): dust-correlated emission excess at 31 GHz.
- Leitch et al. (1997):
  - *emission excess at 14.5 and 31 GHz*
  - Free-free emission from gas $T \geq 10^6$ K?

- Draine & Lazarian 1998:
  - cannot be free-free emission from $10^6$ K gas
  - electric dipole radiation of small dust grains
Past: Ideas of spinning dust emission can be traced through decades of astrophysical research

Erickson 1957
Ginzburg & Eidman 1959
Ferrara & Dettmar 1994

Two big changes from 50s:
1. Discovery of PAHs (Leger & Puget 1984)

Small grains are better emitters:

\[ P \sim \omega^4 \quad \omega \sim r^{-5/2} \quad P \sim r^{-10} \]
PAH molecules observed in interstellar medium

PAH: polycyclic aromatic hydrocarbon

Credit: internet
Electric Dipole Emission from Spinning Dust
(Draine & Lazarian 1998)

Grain of dipole moment $\mu$, rotating with $\omega$ parallel to $a_1$:

- radiates at frequency
  \[ \nu = \frac{\omega}{2\pi} \]

- Emission power:
  \[ P_{\text{ed}}(\omega) = \frac{2}{3} \frac{\mu^2 \omega^4}{c^3} \]

- Angular velocity distribution: $f_\omega \approx \text{Maxwellian}$
Total emissivity integrated over size distribution \( dn/da \):

\[
\frac{j_\nu}{n_H} = \frac{1}{4\pi} \int_{a_{min}}^{a_{max}} da \frac{1}{n_H} \int_{a_{min}}^{a_{max}} \frac{dn}{da} 4\pi \omega^2 f_\omega 2\pi P_{ed}(\omega) \, d\omega
\]

(\( \text{ergs}^{-1}\text{cm}^2\text{sr}^{-1}\text{Hz}^{-1}/\text{H} \))

DL98 model is supported by numerous observations but requires improvement

- Five-year WMAP: bump ~ 40 GHz in Hα-correlated spectrum.
- Dobler et al. (2009) adjusted gas density and dipole moment.

Results are not different from the DL98 model.
Electric Dipole Emission by Precessing Grain

PAH

μ

DL98 model

modeling

our new model

spinning

spinning + precessing

μ

a₁

a₂

a₃

θ
Power Spectrum: Identify Frequency Modes

- Torque-free motion: Euler angles $\phi$, $\psi$, $\theta$, and rates
  \[
  \dot{\phi} = \frac{J}{I_2}, \dot{\psi} = \frac{J \cos \theta (1 - h)}{I_1}
  \]
- Electric dipole moment:
  \[
  \mu(J, \theta, t) = \mu_1 a_1 + \mu_2 a_2
  \]
- Fourier Transform:
  \[
  \ddot{\mu}(J, \theta, t) = \mu_1 \ddot{a}_1 + \mu_2 \ddot{a}_2
  \]
- Power Spectrum:
  \[
  P_{ed,k}(J, \theta) = \frac{2}{3c^3} \sum_i (\ddot{\mu}_{i,k})^2
  \]

Hoang, Draine & Lazarian 10
Power Spectrum: 4 Frequency Modes

- Precessing grain radiates at frequency modes: $\omega_k = \phi, \phi \pm \psi, \dot{\psi}$
- Dominant modes: $\omega_k = \phi \pm \dot{\psi}$

What makes grain rotating?

Hoang, Draine & Lazarian 10
Rotational Damping and Excitation

- H (R~$10^{-7}$/s)
- UV photon (R~$10^{-8}$/s)
- IR emission (~$10^2$ s)
Distribution Function: Solving SDEs

- Angular momentum \( \mathbf{J} \) in the lab system is described by stochastic differential equations (SDEs - Langevin equation):

\[
dJ_i = A_i \, dt + \sqrt{B_{ii}} \, dq_i, \quad i = 1,2,3
\]

\[
A_i = \sum \left\langle \frac{\Delta J_i}{\Delta t} \right\rangle, \quad B_{ii} = \sum \left\langle \left( \frac{\Delta J_i}{\Delta t} \right)^2 \right\rangle, \quad \left\langle dq^2 \right\rangle = dt
\]

- Damping and excitation coefficients \((A_i \text{ and } B_{ii})\) for:
  - dust-neutral and dust-ion collisions
  - infrared emission
  - plasma drag

- Integrate LEs to get \( J(t) \) and find momentum distribution \( f_J \)

- Emissivity per H atom:

\[
\frac{j_v}{n_H} = \frac{1}{4\pi} \frac{1}{n_H} \int da \frac{dn}{da} j^a_v \\
j^a_v = \int pdf(\omega | J) P_{ed}(J) 2\pi f_J dJ
\]
- Peak emissivity increases by a factor $\sim 2$.
- Peak frequency increases by factors $\sim 1.4$ to $1.8$. 

*Hoang, Draine & Lazarian 10*
Emission from Triaxial PAHs

Naphthalene
($\text{C}_{10}\text{H}_8$)

Chrysene
($\text{C}_{18}\text{H}_{12}$)

Pentacene
($\text{C}_{24}\text{H}_{12}$)

Pyrene
($\text{C}_{16}\text{H}_{10}$)

Benzo(g,h,i)perylene
($\text{C}_{22}\text{H}_{12}$)

Coronene
($\text{C}_{24}\text{H}_{12}$)

Triaxial body shape!

Disk-like shape
Multiple frequency modes:

\[ \omega_m = \langle \dot{\phi} \rangle + m \langle \dot{\psi} \rangle, m = 0, \pm 1, \pm 2, \ldots, \]

\[ \omega_n = n \langle \dot{\psi} \rangle, n = 0, 1, 2 \]

where \(<\ldots>\) denotes time averaging.

\[ q = \frac{2I_1E_{rot}}{J^2} \]

\[ \frac{\text{IFT}^2}{\text{max}(\text{IFT}^2)} \]

\[ \text{DL98} \]

Hoang, Lazarian, & Draine 11
Emissivity Increases with Grain Irregularity

- Working model: Simple irregular shape
- Irregularity: $\eta = b_3 / b_2$
Impulsive excitation by single-ion collisions extends the tail.

Change in $J$ may be large.

\[
\frac{\omega}{\omega_{T,II}} \quad \frac{\omega}{\omega_{T,II}}
\]

WIM
\[
\begin{align*}
\alpha &= 4.0 \ \text{Å} \\
\text{with impulses} \\
\text{without impulses}
\end{align*}
\]

$\frac{j_0}{n_{H}}$ (Jy sr$^{-1}$ cm$^{-2}$ H)

\[
10^{-17} \quad 10^{-18}
\]

$\nu$ (GHz)

Ali-Haimoud et al.

with impulses

no impulses
Fitting to WMAP data from H I cloud

\[ \frac{I_v^{\text{mod}}}{T_{94\text{GHz}}} = Sd_0 \frac{I_v^{\text{sd}}(\text{CNM})}{T_{94\text{GHz}}} + C_0 \left( \frac{\nu}{23\text{GHz}} \right)^2 + T_0 \left( \frac{\nu}{94\text{GHz}} \right)^{3.8} \]

- \( T_0 = 0.8 \)
- \( Sd_0 \sim 0.9 \)
- \( \beta_0 = 0.95 \) D,
- \( n_H \sim 10 \text{ cm}^{-3} \)

Hoang, Lazarian, & Draine 11
More regions with AME discovered by Planck

Credit: Planck
Perseus cloud

(Planck team 2011)
Magnetic dust: Emission from Magnetic Dipole Fluctuations

- Draine & Lazarian (1999) proposed magnetic dipole microwave emission as an alternative to spinning dust.


![Graph showing submillimeter wavelength spectrum with various data points and lines representing different models.](image-url)
Polarization of Thermal Dust and Spinning Dust Emission

• What is dust polarization? Why do we care?
• Grain Alignment Theory
• Ab-initio Modeling of Polarization vs. Observations
• Inversion Technique and Self-consistent Modeling
Polarization of Light From Distant Stars by Interstellar Medium

W. A. Hiltner
Yerkes Observatory, University of Chicago

In the course of photometric observations made last summer with the 82-inch telescope of the McDonald Observatory (University of Texas) the writer found that the light from distant galactic stars is polarized. Polarizations as high as 12 percent were found. The plane of polarization appears to be close to the galactic plane in the cases examined. More recently control measures were made at the Lick Observatory, thanks to the courtesy of Director Shane and Dr. G. Kron; and during December the work at the McDonald Observatory was extended to different regions of the Milky Way.

In view of the unexpected nature of this result the circumstances leading to its discovery are recorded. Photometric observations for the detection of partially polarized phenomena in eclipsing binary stars have been in progress at the Yerkes Observatory for several years with a view to establishing observationally the effect pointed out by Chandrasekhar that the continuous radiation of early-type stars should be polarized. On the assumption that the opacity of early-type stars is due to scattering by electrons, the continuous radiation emerging from a star should be polarized with a maximum of polarization of 11 percent at the limb. Since the presence of this polarization can be detected only when the early-type star is partially eclipsed by a larger-type companion of the system, the effect is masked by radiation from this companion so that the expected maximum observable effect was only of the order of 1 percent in one case investigated (R Y Persei).

At this stage Dr. John Hall, of Amherst College, proposed to the writer a program of collaboration whereby Dr. Hall would construct a "flicker" photometer which was to be tested jointly at the McDonald Observatory. Independently the writer was developing his own equipment which used polaroids. Dr. Hall's equipment was tested in August 1947, during a short session at the McDonald Observatory, but no dependable results were obtained and it was found that the equipment had to be remodeled. Unfortunately, Dr. Hall was unable to come for a second trial period, scheduled for August 1948.

Meanwhile the writer's own equipment was completed and put into use during the summer of 1948 and was found satisfactory. Certain Wolf Rayet stars which were known or suspected to be eclipsing binaries were examined for polarization. Fairly large polarizations were found, but they did not appear to depend on the phase of the binary motion. The possibility of instrumental polarization was considered, of course, but ruled out by control measures on check stars. The Wolf Rayet stars give the following results:

<table>
<thead>
<tr>
<th>Star</th>
<th>% Polarization</th>
<th>Position angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CQ Cep</td>
<td>10.0</td>
<td>62°</td>
</tr>
<tr>
<td>BD 55 2721</td>
<td>8.9</td>
<td>44</td>
</tr>
<tr>
<td>WN 8</td>
<td>12.5</td>
<td>44</td>
</tr>
</tbody>
</table>

Coordinates: 22°08′+57°26′ (1945); 12.5 magnitude.

The control stars had similar color and brightness, but showed no polarization except for one object, BD 55 2723, which gave 3 percent. This star, however, is a giant and more distant than the other control stars. Similar observations made on a group of Wolf Rayet stars in Cygnus showed no appreciable polarization, while two stars in Scutum gave positive results. Other regions, such as the double cluster in Perseus, also show polarization with values ranging up to 12 percent.

We conclude from the positive and negative results quoted that the measured polarization does not arise in the atmospheres of these stars but must have been introduced by the intervening interstellar medium. If the interstellar medium is photoelectrically opaque (as indicated by Kennicutt), a solar-type star is not detectably polarized through 0.5, but a Wolf-Rayet or a C-type supergiant is probably detectably polarized to a degree of a few percent. Further observations are in progress for relating this phenomenon with other observable characteristics of interstellar medium. As has been stated, the results already at hand indicate that the plane of polarization approximates the plane of the galaxy.

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Observations of the Polarized Light From Stars

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

Photometric observations of the polarization of starlight made during the summer of 1948 have shown that the light from a star contains a small amount of linear polarization which is produced by interstellar matter. Furthermore, the percentage of polarization appears to be independent of wavelength and the plane of polarization is determined by the angle at which the star is observed. A strong correlation is observed between the percentage of polarization and the angle of observation. The observations were obtained with a photoelectric polarimeter (P) built at Amherst College.

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ISM as a polarizer
Polarization Spectrum of Starlight

\[ p(\lambda) = p_{\text{max}} \exp \left[ -K \ln^2 \left( \frac{\lambda_{\text{max}}}{\lambda} \right) \right] \]

\( K = 1.15 \), Serkowski et al. 1973, 1975

\( K = 1.66\lambda_{\text{max}} + 0.01 \) (Whittet + 92)

\( \lambda_{\text{max}} \approx 0.55 \mu m \)
Gravitational Waves via B-mode Polarization
Separating Polarized CMB Components

The simplest and most economical remaining interpretation of the $B$-mode signal which we have detected is that it is due to tensor modes — the IGW template is an excellent fit to the observed excess. We therefore proceed to set a constraint on the tensor-to-scalar ratio and find $r = 0.20^{+0.07}_{-0.05}$ with $r = 0$ ruled out at a significance of 7.0σ. Multiple lines of evidence have been presented that foregrounds are a subdominant contribution: i) direct projection of the best available foreground models, ii) lack of strong cross correlation of those models against the observed sky pattern (Figure 6), iii) the frequency spectral index of the signal as constrained using BICEP1 data at 100 GHz (Figure 8), and iv) the spatial and power spectral form of the signal (Figures 3 and 10).

Subtracting the various dust models and re-deriving the $r$ constraint still results in high significance of detection. For the model which is perhaps the most likely to be close to reality (DDM2 cross) the maximum likelihood value shifts to $r = 0.16^{+0.06}_{-0.05}$ with $r = 0$ disfavored at 5.9σ. These high values of $r$ are in apparent tension with previous indirect limits based on temperature measurements and we have discussed some possible resolutions including modifications of the initial scalar perturbation spectrum such as running. However we emphasize that we do not claim to know what the resolution is.
Planck intermediate results. XXX.
The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes

ABSTRACT

ound present in measurements of the polarization of the cosmic xploit the uniqueness of the Planck HFI polarization data from 100 over the multipole range $40 < \ell < 600$ well away from the Galactic and allow a precise determination of the level of contamination for of Galactic dust, we show that general statistical properties of the gular power spectra. The polarization power spectra of the dust are $2.42 \pm 0.02$. The amplitudes of the polarization power spectra vary frequency dependence of the dust polarization spectra is consistent e lowest Planck HFI frequencies. We find a systematic difference e verify that these general properties are preserved towards high test dust-emitting regions there are no “clean” windows in the sky out subtraction of foreground emission. Finally, we investigate the experiment. Extrapolation of the Planck 353 GHz data to 150 GHz ipole range of the primordial recombination bump ($40 < \ell < 120$); certainty $(+0.28, -0.24) \times 10^{-2} \mu K^2_{\text{CMB}}$ from the extrapolation. This ghts the need for assessment of the polarized dust signal even be reduced through an ongoing, joint analysis of the Planck and
Dust polarization used to test star formation theory

- Chandrasekhar-Fermi technique:

\[
\frac{B_{\text{POS}}}{\sqrt{4\pi\rho}} \propto \frac{\delta V}{\delta \phi}
\]

- Mass to Flux ratio:

\[
\frac{E_{\text{gra}}}{E_{\text{mag}}} = \frac{M}{\Phi} \sim \frac{N(\text{HI})}{B}
\]

- \( M/\Phi \) and B-field and outflow allow us to test star formation theory
Not only to interpret observations but we must have predictive model, as well as quantitative predictions for CMB component separation. Therefore, a combination of various approaches is needed.
Dust grains must be aligned to produce starlight polarization.

Polarization produced by differential extinction by aligned dust grains

Credit: A. Goodman
Small grains (PAH) \textit{weakly} aligned by paramagnetic relaxation.

- Rotating magnetization by $B_{\text{perp}}$ induces energy dissipation, decreasing the angle between $J$ and $B$.

\textbf{ISM}

\[
\tau_{\text{DG}} \approx 1.2 \times 10^6 \left( \frac{B}{5\,\mu G} \right)^{-2} \left( \frac{a}{0.1\,\mu m} \right)^2 \left( \frac{K(\omega)}{1.2 \times 10^{-13}\,s} \right)^{-1} \text{yr}
\]

\[
\tau_{\text{drag}} \approx 6.3 \times 10^4 \left( \frac{a}{0.1\,\mu m} \right) \left( \frac{1}{1 + F_{\text{IR}}} \right) \text{ yr}
\]

\[
\frac{\tau_{\text{DG}}}{\tau_{\text{drag}}} \approx 20 \left( \frac{a}{0.1\,\mu m} \right) (1 + F_{\text{IR}})
\]

$\tau_{\text{DG}} < \tau_{\text{drag}}$ for $a \ll 0.1$ \,\mu m grains.

- Small grains can be aligned, big grains not.
Theoretical calculations of paramagnetic alignment

• Evolution of angular momentum $\mathbf{J}$ in the lab frame:

$$dJ_i = A_i dt + \sqrt{B_{ii}} dq_i, \ i = 1 - 3$$

$$A_i = \sum_k \left< \frac{\Delta J_i^k}{\Delta t} \right>, B_{ii} = \sum_k \left< \frac{(\Delta J_i^k)^2}{\Delta t} \right>, \left< dq^2 \right> = dt$$

• Damping and excitation coefficients ($A_i$ and $B_{ii}$) for:
  - dust-neutral and dust-ion collisions
  - infrared emission
  - plasma drag
  - paramagnetic relaxation, i.e., $\tau_{DG}(B)$

• Degrees of alignment:

$$R = \langle G_x^* G_j \rangle, \ Q_J(J,B) = \langle G_j \rangle, \ Q_X(a_1,J) = \langle G_X \rangle$$

with $G_j = [3\cos^2\beta - 1]/2$, $G_X = [3\cos^2\theta - 1]/2$
Paramagnetic alignment increases with magnetic strength.

Hoang et al. 2014b
Big grains are aligned by radiative torques acting on helical grains.

- Draine & Weingartner 1997
- Lazarian & Hoang 2007
- Lazarian & Hoang 2007a

[Diagram showing shapes 1, 2, and 3 with labels for numeric and analytical model]

- Efficiency graph:
  - Lazarian & Hoang 07

- Max rotational rate graph:
  - Hoang & Lazarian 09
Basic Properties of RAT Alignment:
Grains are aligned with low-J and high-J attractors.

- Grains at high-J attractors are perfectly aligned, those at low-J attractors are partially aligned.
- AMO predicts the “right” alignment with long axes perpendicular to $B$. 

$Q_{\text{max}}$-ratio = 0.78

DDSCAT

AMO, $\psi = 70^\circ$, thermal fluctuations

$Q_{\text{max}}$-ratio = 0.78

Hoang & Lazarian 08
"Ab Initio" Modeling of Dust Polarization

- Grain size, shape, $n_{\text{gas}}$, $T_{\text{gas}}$, radiation field (intensity, $k$ and $B$ angle), and $Q^{\text{max}}$-ratio

**Theory**

- Critical size of aligned grains: $a_{\text{ali}}$
- Degree of grain alignment: $R$

\[
\frac{\sigma_{\text{pol}}}{N_H} = \frac{a_{\text{max}}}{a_{\text{ali}}} \left( C_\perp - C_\parallel \right) \frac{n_d(a)R(a)\cos^2 \gamma}{2}
\]
Polarization from Starless Cloud

DG theory: grains aligned in interface, not core

\[ A_V \sim 3 \]

RAT model

\[ A_V = 10 \]

Whittet, Hough, Lazarian, Hoang (2008)
Reflection Nebula: IC 63

Hoang et al. 2014b
Polarized Emission from Molecular Clouds

Hoang et al. 2015

weak turbulence

sub-Alfvenic turb.

strong turbulence

super-Alfvenic turb.

Vaillancourt et al. 2008

M17

W51

GMC-1

DR21

GMC-3

350 μm

350 μm

model 1: starless core
model 1: 1 star, X=1
model 3: 3 stars, X=3
model 4: 3 stars, X=30
model 5: 3 stars, X=300
model 5: 3 stars, X=300
Constraining Polarization of Spinning Dust from Starlight Polarization

PAHs produce 2175 Å (e.g., Draine 89)

PAHs radiate spinning dust emission

How efficient are PAHs aligned?

December 26, 2014

P ∝ \langle Q_J(J,B)Q_X(a,J)\rangle \cos^2 \xi

Cardelli et al. 89

Wolff et al. 1993

extinction

2175 Å bump

polarization

2175 Å bump

typical ISM

P/\text{max}

0.8

0.6

0.4

0.2

0

1 / \lambda (\mu m^{-1})

P/\text{max}

0.8

0.6

0.4

0.2

0

1 / \lambda (\mu m^{-1})

\text{Extinction Curves}

2.75

3.1

4.0

R_v=5.5

visual/near-UV

far-UV rise

\lambda^{-1} (\mu m^{-1})

2175 Å bump
Inversion Technique

- Adopting a model of dust: silicate & carbonaceous compositions
- Constructing a model (Kim & Martin 95, Draine & Fraisse 09):

\[
A_{\text{mod}}(\lambda_k) \propto \sum_{m=\text{sil,carb}}^{Na-1} \sum_{i=0}^{Na-1} n_d(a_i)\pi a_i^2 Q_{\text{ext}}(a_i, \lambda_k)
\]

\[
P_{\text{mod}}(\lambda_k) \propto \sum_{m=\text{sil,carb}}^{Na-1} \sum_{i=0}^{Na-1} f(a_i)n_d(a_i)\pi a_i^2 Q_{\text{pol}}(a_i, \lambda_k)
\]

- Minimizing an objective function:

\[
\chi^2_{\text{ext}} = \sum_{k=0}^{N_\lambda - 1} w_{\text{ext}}\left[A_{\text{mod}}(\lambda_k) - A_{\text{obs}}(\lambda_k)\right]^2
\]

\[
\chi^2_{\text{pol}} = \sum_{k=0}^{N_\lambda - 1} w_{\text{pol}}\left[P_{\text{mod}}(\lambda_k) - P_{\text{obs}}(\lambda_k)\right]^2
\]

\[
\chi^2 = \chi^2_{\text{ext}} + \chi^2_{\text{pol}} + \chi^2_{\text{constraints}}
\]

Model parameters:

- \(n_d(a_i)\): grain size distribution
- \(f(a_i)\): alignment function

- Nonlinear Chi-square fitting: \(\sim N_a \cdot N_\lambda\) free parameters
- Monte Carlo search method for global minimization

Hoang et al. 2014a
• PAHs are very weakly aligned
• Big silicates are efficiently aligned.
Maximum polarization of spinning dust is ~ 1.6 percent.

Future polarization data will test our predictions.
1. Spinning dust emission becomes a new, accepted foreground.
2. A comprehensive model of spinning dust is established.
3. Spinning dust can be used to probe PAH physical parameters using observational data (e.g., Planck, coming SKA).
4. Spinning Dust Emission is very weakly polarized, but Thermal Dust Emission is highly polarized.
5. A predictive model of grain alignment is proposed and supported by numerous observations.
6. Combination of observations, theory and inversion technique is needed for precision modeling of dust polarization.

Thank you for your listening!