Dust Polarization in the Microwave: Challenges on the Quest for B-Modes

Brandon Hensley
Jet Propulsion Laboratory,
California Institute of Technology

In collaboration with
Bruce Draine (Princeton)
Aaron Meisner (LBL)

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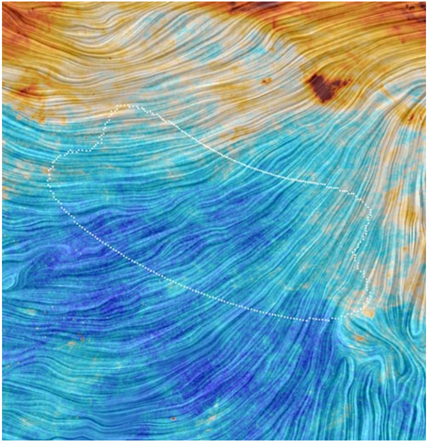
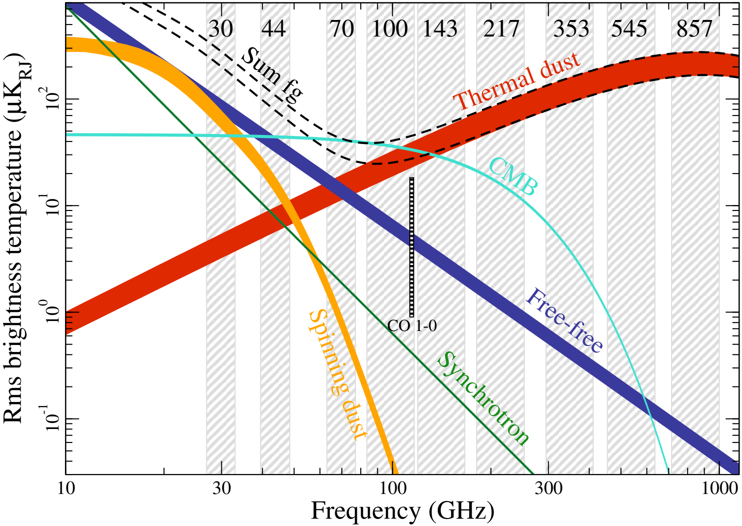
The Quest for Primordial B-Modes



Credit: ESA/*Planck*

The Microwave Sky in Intensity

Planck 2015 X



Why is Dust Emission Polarized?

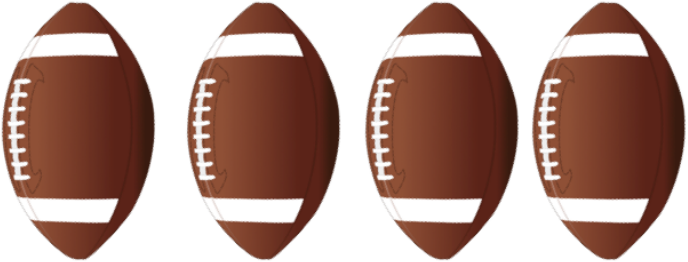
Two ingredients required:

1. Grains must be aspherical
2. Grains must be aligned

Grain Shape

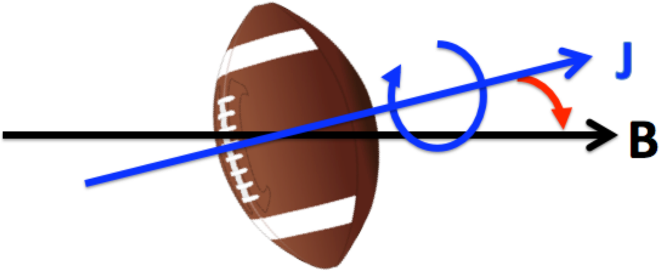
Grain Alignment

Grain Alignment



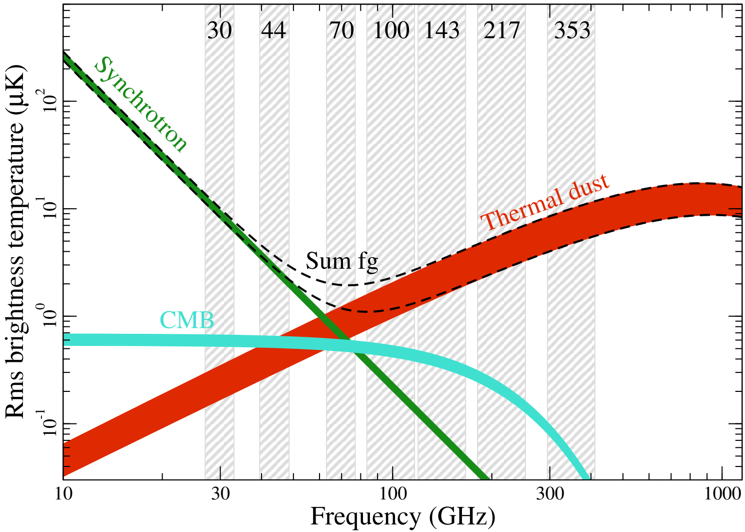
Grain Alignment

Grain spins about $\vec{\mathbf{J}}$
$\vec{\mathbf{J}}$ systematically aligns with $\vec{\mathbf{B}}$



The Microwave Sky in Polarization

Planck 2015 X



Key Questions

- Could the AME be polarized?
  (and do we really know what it is?)

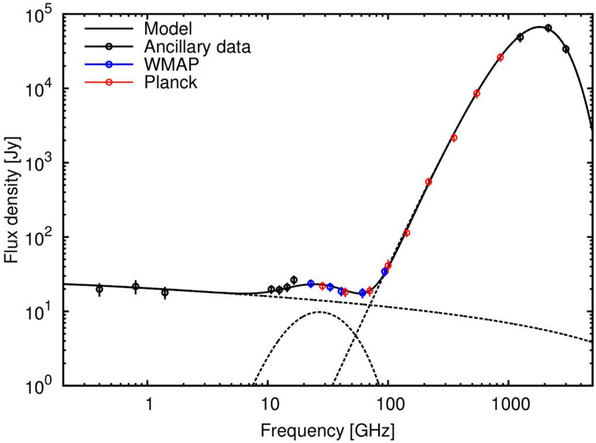
- What is the frequency-dependence of the dust polarization? Is it the same as total intensity?

Part I

- PAHs and the AME
- Hensley, Draine, and Meisner 2015. Submitted to ApJ arXiv:1505.02157

Anomalous Microwave Emission

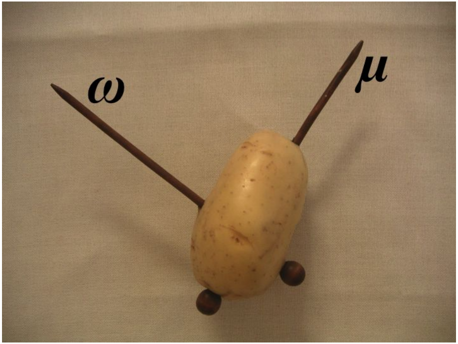
- Discovery of a dust-correlated “bump” in emission (Kogut et al 1996, Leitch et al 1997, de Oliveira-Costa et al 1997)



Planck Collaboration 2011

Spinning Dust Physics

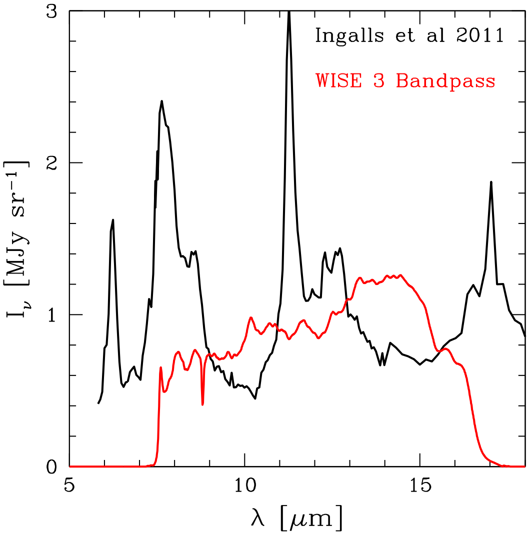
- AME can be explained by spinning dust grains (Draine & Lazarian 1998ab)
- Very small grains (e.g. PAHs) can get spun up by gas collisions, radiative torques, and other processes
- If grains have a dipole moment, this rotation causes them to radiate



Credit: Yacine Ali-Haïmoud

PAHs

- Attractive AME carrier because they are small and ubiquitous
- Abundance traced by IR emission features at 8 and 12 μm



Spinning Dust Emissivity

Galactic spinning dust emissivity

$$j_{\nu,\ 30\ \mathrm{GHz}}/n_H = 3 \times 10^{-18}\ \mathrm{Jy\ cm^2\ sr^{-1}\ H^{-1}}$$

Emissivity per PAH fairly robust to environmental conditions, so assume a linear scaling with Σ_{PAH}

$$\boxed{I^{\mathrm{AME}}_{\nu,\ 30\ \mathrm{GHz}} = 1.0 \left(\frac{\Sigma_{\mathrm{PAH}}}{M_\odot\ \mathrm{kpc}^{-2}}\right)\ \mathrm{Jy\ sr^{-1}}}$$

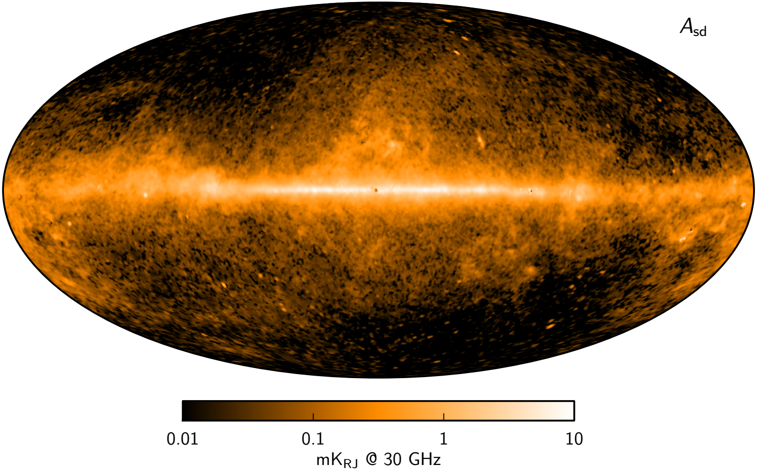
Spinning Dust Theory

Warning: Reality may not be so simple

Full-Sky Test of the Spinning PAH Hypothesis

Full-sky maps of the AME derived from component separation of the microwave sky by *Planck* let us test the AME-PAH connection in detail.

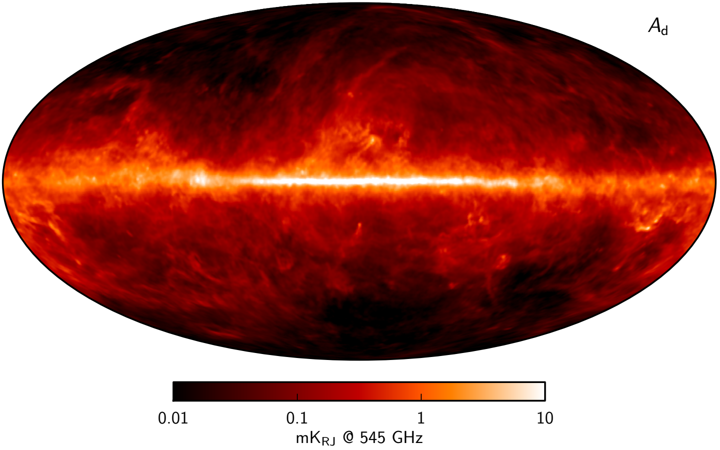
$I_\nu^{\rm AME}$



Planck 2015 X

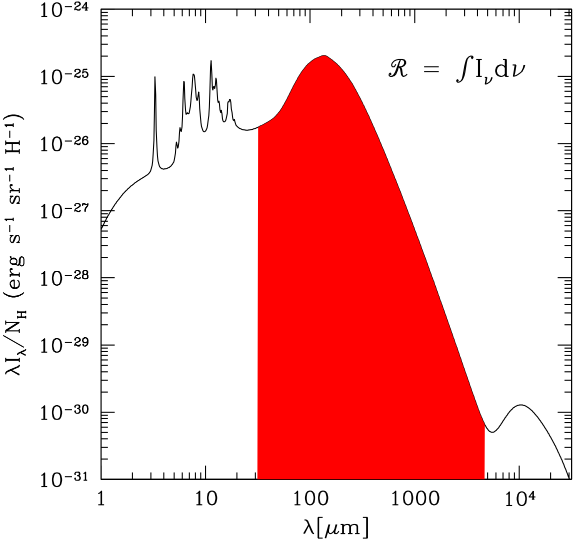
τ_{353}

$$I_\nu = \tau_\nu B_\nu(T_d)$$
$$\tau_\nu = \kappa_\nu M_d$$



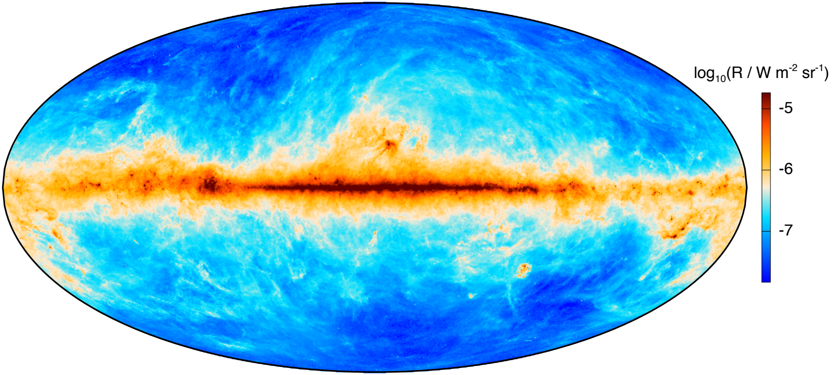
Planck 2015 X

$\mathcal{R}$



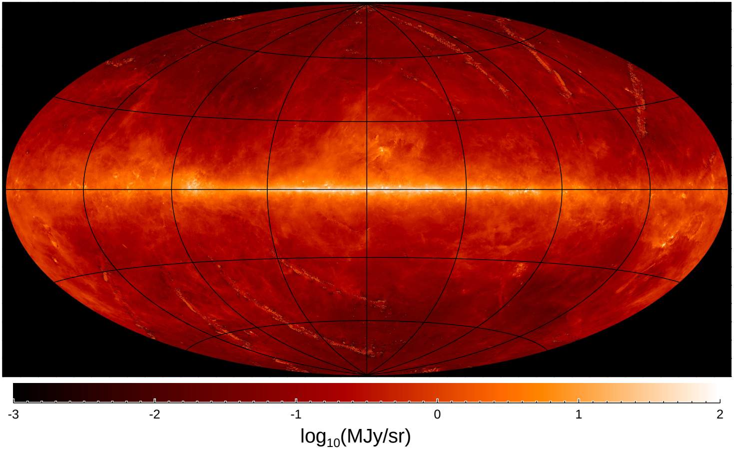
$\mathcal{R} = \int I_\nu d\nu$
$\lambda I_\lambda / N_H$ (erg s^{-1} sr^{-1} H^{-1})
$\lambda[\mu m]$
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
1
10
100
1000
10^4

$\mathcal{R}$



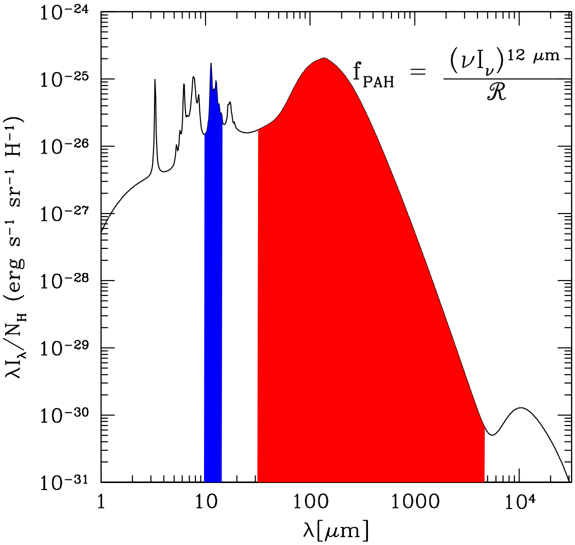
Planck 2013 XI

$I_\nu^{12\,\mu\mathrm{m}}$



Meisner & Finkbeiner 2014

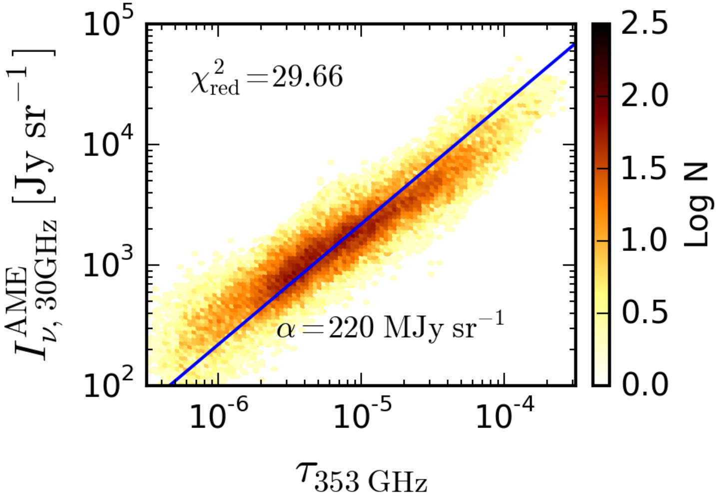
$f_{\rm PAH}$


10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
$\lambda I_\lambda / N_H$ (erg s^{-1} sr^{-1} H^{-1})
1
10
100
1000
10^4
$\lambda[\mu m]$
$f_{\rm PAH} = \frac{(\nu I_\nu)^{12\ \mu m}}{\mathcal{R}}$

Model Predictions

1. Linear correlation with τ_{353}
2. Even tighter correlation with $f_{\rm PAH}\tau_{353}$
3. No strong correlation with radiation field

Correlation with τ_{353}



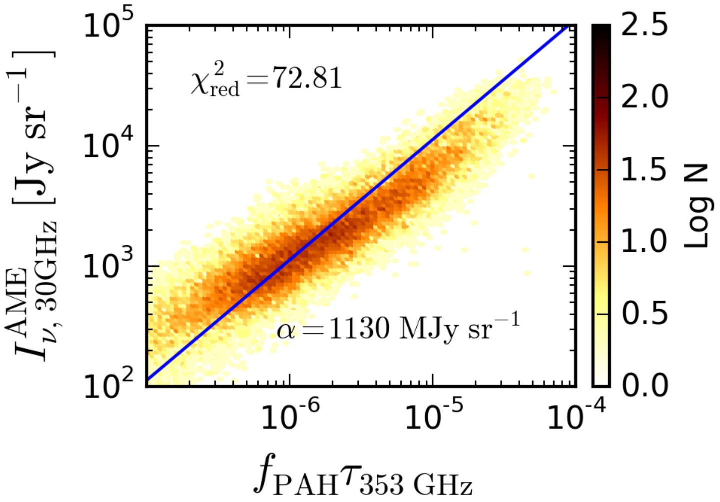
Model Predictions

✓ Linear correlation with τ_{353}

2 Even tighter correlation with $f_{\rm PAH}\tau_{353}$

3 No strong correlation with radiation field

Correlation with $f_{\mathrm{PAH}}\tau_{353}$



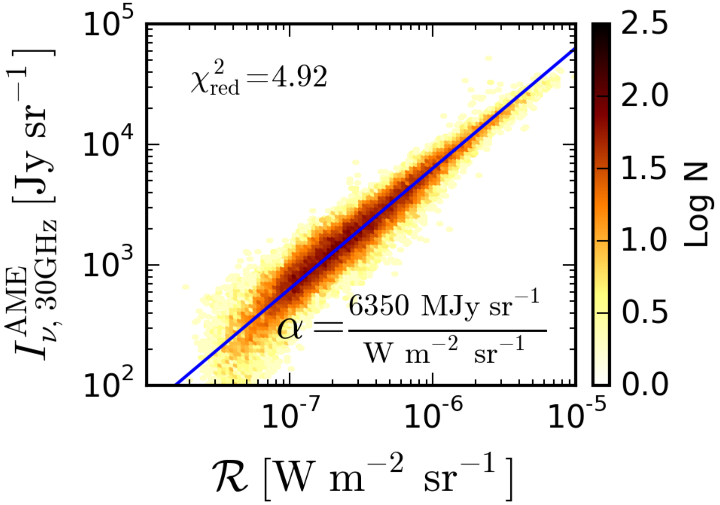
Model Predictions

✓ Linear correlation with τ_{353}

X Even tighter correlation with $f_{\mathrm{PAH}}\tau_{353}$

3 No strong correlation with radiation field

Correlation with $\mathcal{R}$



Model Predictions

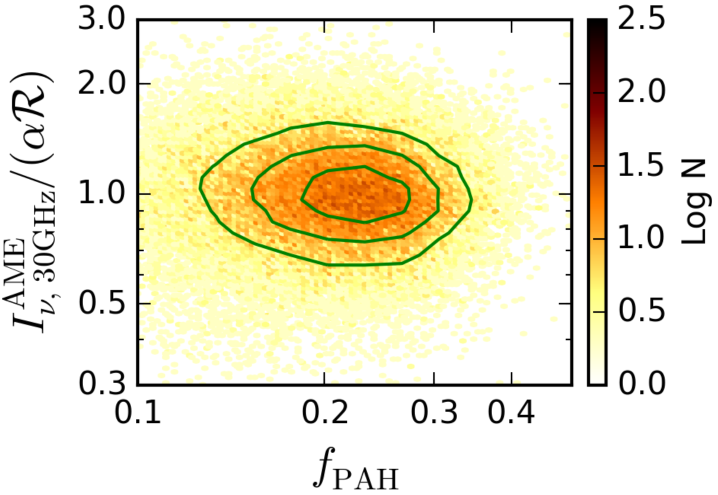
- ✓ Linear correlation with τ_{353}
- X Even tighter correlation with $f_{\mathrm{PAH}}\tau_{353}$
- X No strong correlation with radiation field

A Further Test

- Does PAH abundance explain fluctuations in AME/$\mathcal{R}$?

Correlation with $f_{\rm PAH}\mathcal{R}$

- $f_{\rm PAH}$ does **NOT** improve the correlation with $\mathcal{R}$

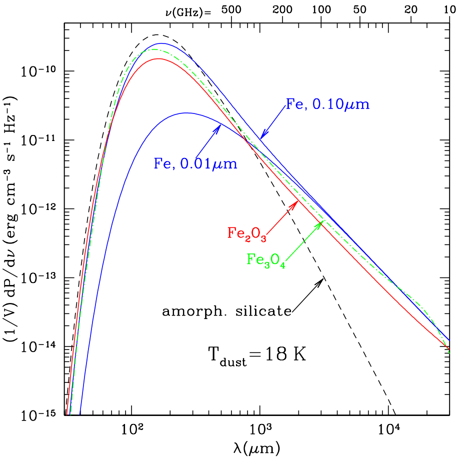


Alternate Models

- What are our next-best theories?

Magnetic Nanoparticles

- **Emissivity per unit volume** of 0.01μm grains heated to 18K
- Emissivity in mm and sub-mm much stronger than amorphous silicate grains



Draine and Hensley 2013

Some Problems...

- Not great at reproducing the shape of the SED
- Emission would likely be strongly polarized, in conflict with observations

Spinning Non-PAHs

- Still spinning dust, just not PAHs
- Not clear whether including a sufficient number of ultrasmall grains of a different type (e.g. silicates) would violate other constraints (e.g. UV extinction)

No Spinning PAH Emission?

- Invoking alternate explanation still requires asking why the PAHs *aren't* producing significant spinning dust emission
- Electric dipole moments overestimated?

Conclusions

- No apparent link between AME and PAHs, other carriers and other mechanisms should be (re)considered
- New data is needed to better separate AME from other emission
- Major blind spot in our knowledge of Galactic microwave emission– puzzle needs to be solved!

Part II

- New Models of Interstellar Dust (with Polarization!)
- Hensley & Draine 2016. In prep.

Big Picture

- Grains producing polarized emission in the IR are **the same grains** that produce polarized extinction in the optical
- Use multi-wavelength data to construct a **physical** model of dust compatible with the observations

Method

1. Collect latest observations on dust in diffuse ISM– **extinction** (total and polarized), **emission** (total and polarized), and abundances
2. Identify candidate grain materials, grain shapes, and grain sizes that can reproduce the observations
3. Assess the observational consequences of different models

Composition Effects

Grains are of different composition appear to have different polarization properties

- Silicate Features– Polarization detected
- Carbonaceous Features– Unpolarized

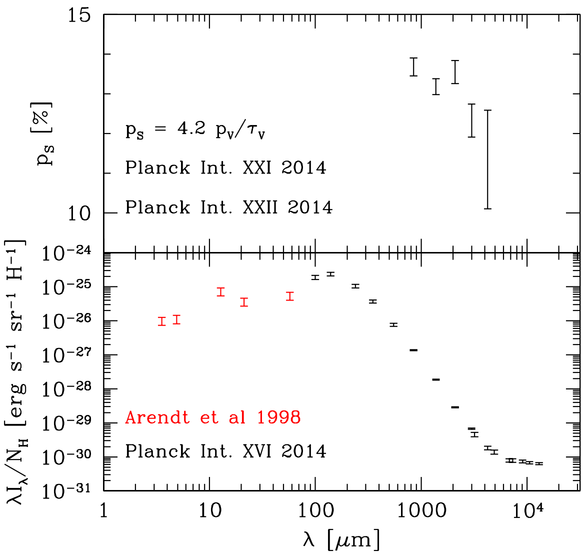
Composition Effects

> "We find that fitting a single modified blackbody component for the thermal dust where the "real" sky should account for two dust components may strongly bias the estimation of the tensor-to-scalar ratio by more than 5σ"
>
> — Remazeilles et al 2015

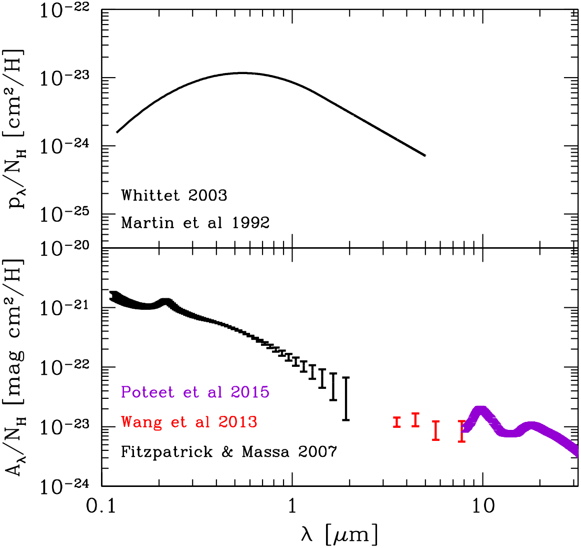
Observational Constraints

What observations does a successful dust model need to reproduce?

Emission Constraints

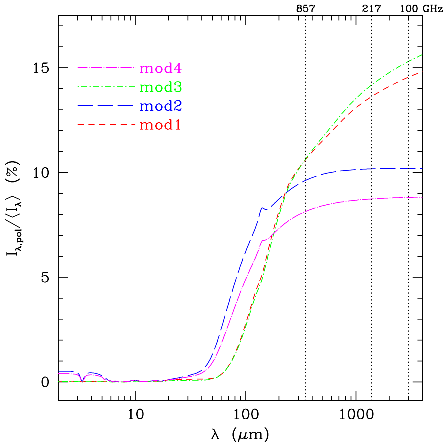


Extinction Constraints



Draine and Fraisse 2009

- Used Draine and Li dust materials to make predictions for polarized emission in the *Planck* bands
- Model predicts too much extinction per unit emission (Planck Int XXIX 2014)

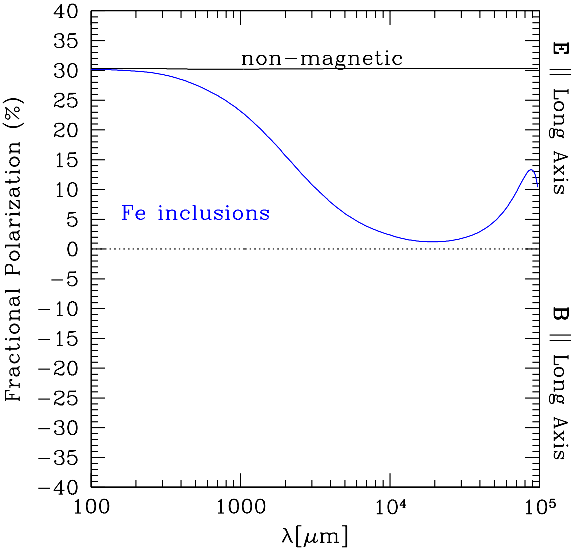


Draine and Fraisse 2009

Polarized Dust Emission

- Models with silicate and carbonaceous grains alone have difficulty reproducing the observed decline in the polarization fraction with increasing wavelength
- A new ingredient– magnetic nanoparticles

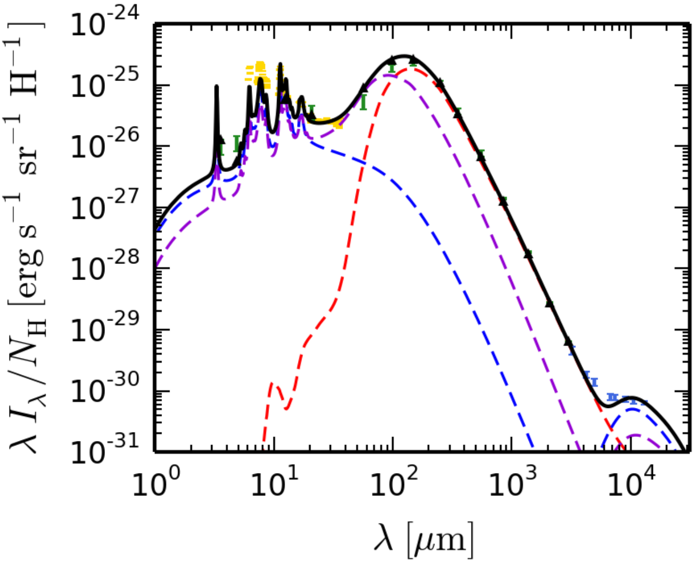
Magnetic Nanoparticles



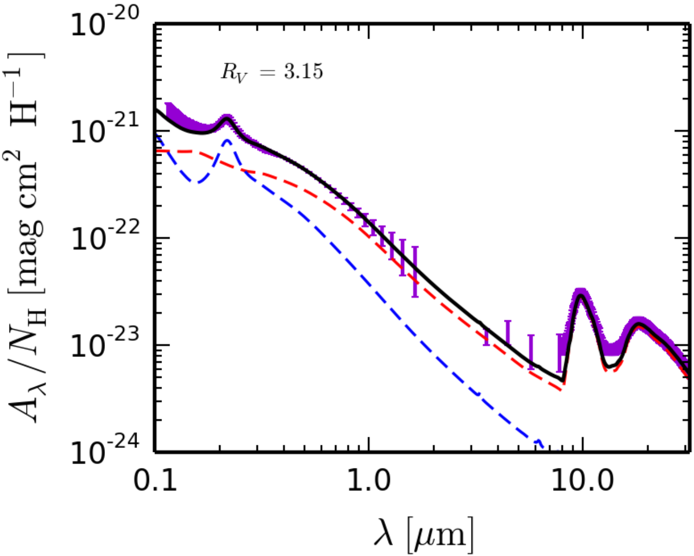
Example

- 2:1 spheroidal silicate grains with 5% iron nanoparticles by volume as inclusions
- Unaligned carbonaceous grains
- PAHs

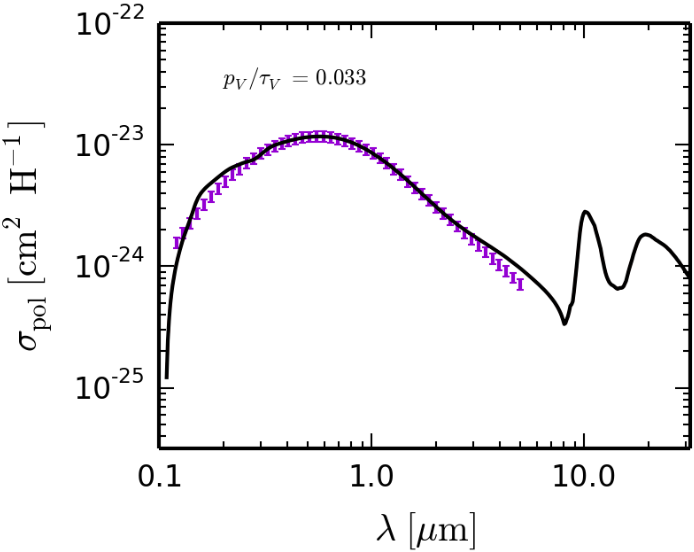
Emission


$\lambda I_\lambda / N_H$ [erg s^{-1} sr^{-1} H^{-1}]
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^0
10^1
10^2
10^3
10^4
λ [μm]

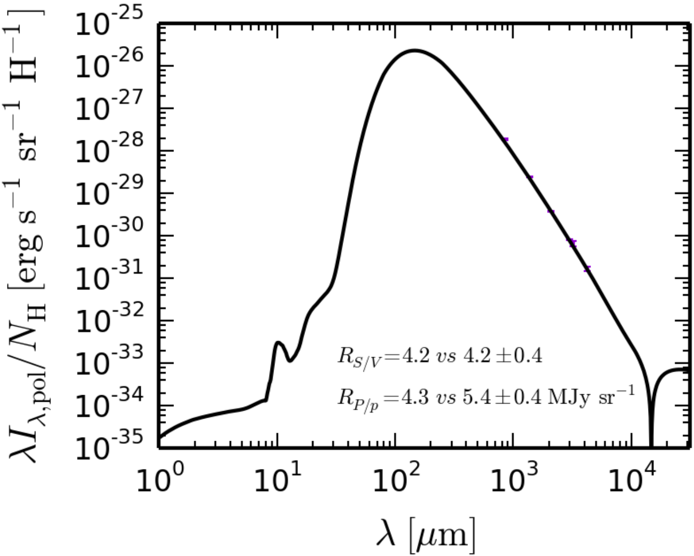
Extinction


$R_V = 3.15$
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
0.1
1.0
10.0
A_λ / N_H [mag cm^2 H^{-1}]
λ [μm]

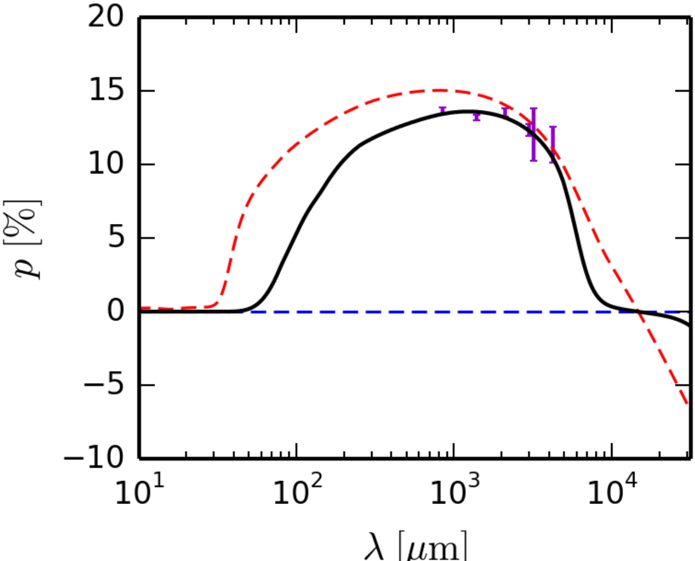
Polarized Extinction



Polarized Emission



Polarization Fraction



Summary

- Inclusion of iron grains allows us to match the frequency-dependence of the polarized emission
- We alleviate the tension between emission and extinction in the Draine and Li 2007 model by making silicates more emissive at long wavelengths

With a Model, We Can...

- Test the model against the *Planck* sky and learn what drives variations in dust properties
- Predict dust properties at all wavelengths given a model fit
- Simulate different realizations of dust properties and the implications for component separation

Conclusions

- Fluctuations in AME/$\mathcal{R}$ are uncorrelated with $f_{\rm PAH}$, casting doubt on the association of AME and PAHs
- Uncovering the nature of the AME is important for understanding microwave foregrounds– more observations and analyses are needed!
- Our new models of interstellar dust successfully reproduce the mean properties of dust in the diffuse ISM, including in polarization
- The new models enable future work on the properties of Galactic dust as well as next-generation component separation