Astro2020 Science White Paper

Determining the Composition of Interstellar Dust with Far-Infrared Polarimetry

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☑ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:

Name: Brandon Hensley
Institution: Princeton University
Email: bhensley@astro.princeton.edu

Co-authors: Peter Ashton[7,11,15], François Boulanger[9], David T. Chuss[20], Susan E. Clark[5], Jacques Delabrouille[1,8], B. T. Draine[14], Hans Kristian Eriksen[18], Laura Fissel[12], Raphael Flauger[16], Aurelien Fraisse[14], Vincent Guillet[4,10], Al Kogut[2], C. R. Lawrence[6], Alex Lazarian[19], Daniel Lenz[6], Giles Novak[13], Mathieu Remazeilles[17], Ian Stephens[3], Ingunn Wehus[18], Andrea Zonca[16]

Abstract: Does interstellar dust come in distinct silicate and carbonaceous varieties, or are interstellar grains a homogeneous mishmash of different materials? State-of-the-art spectropolarimetry of dust extinction features, measurements of the far-infrared dust SED, and determinations of the submillimeter dust polarization fraction as a function of frequency appear to be telling conflicting stories. In this white paper, we argue that sensitive far-infrared dust polarimetry in the 100–850 μm wavelength range can provide a definitive test of the multi-component dust paradigm, with far-reaching implications from the evolution of metals in the interstellar medium to strategies for component separation in Cosmic Microwave Background experiments. We also advocate for the construction of polarized dust SEDs over small sky regions at ground-accessible frequencies below 353 GHz to test for grain components like magnetic nanoparticles and the presence of polarized anomalous microwave emission. Finally, we argue that a renewed interest in spectropolarimetry in the dust extinction features at 3.4, 9.7, and 18 μm would be a timely complement to FIR polarimetry to elucidate the physical properties of interstellar dust.

[1]CEA Saclay DSM/Irfu
[2]Goddard Space Flight Center
[3]Harvard-Smithsonian Center for Astrophysics
[4]Institut d'Astrophysique Spatiale, CNRS, Univ. Paris-Sud, Université Paris-Saclay
[5]Institute for Advanced Study
[6]Jet Propulsion Laboratory, California Institute of Technology
[7]Kavli Institute for the Physics and Mathematics of the Universe
[8]Laboratoire Astroparticule et Cosmologie (APC), CNRS/IN2P3
[9]Laboratoire de Physique de l'ENS, Université PSL, CNRS
[10]Laboratoire Univers et Particules de Montpellier, Universite de Montpellier, CNRS/IN2P3
[11]Lawrence Berkeley National Laboratory
[12]National Radio Astronomy Observatory
[13]Northwestern University
[14]Princeton University
[15]University of California, Berkeley
[16]University of California, San Diego
[17]University of Manchester
[18]University of Oslo
[19]University of Wisconsin-Madison
[20]Villanova University

1 Introduction to Dust Composition

The elemental composition of interstellar dust is reasonably well-determined. By comparing the elemental abundances in the gas phase from absorption spectroscopy to interstellar abundances inferred from stellar spectroscopy, one finds that much of the interstellar C, O, Si, Mg, and Fe must be locked in macroscopic solids, i.e. dust (Jenkins, 2009). The key and largely unresolved question is into what specific materials these elements are assembled.

Interstellar dust has several spectroscopic features that help elucidate its chemical composition. It is well-established that hydrocarbons constitute some of the dust material. Strong mid-infrared emission features have been identified with aromatic nanoparticles (polycyclic aromatic hydrocarbons, PAHs). A prominent, broad extinction feature at 2175 Å is thought to arise from sp^2-bonded carbon, perhaps in PAHs or in graphite. The strong 3.4 μm extinction feature indicates aliphatic (i.e., chain-like) CH bonds, while its absence in emission implies that is carried by grains larger than the PAHs.

Likewise, it is well-established that amorphous silicate is an important component of interstellar dust as attested by strong extinction features at 9.7 and 18 μm. The exact stoichiometry is unknown, though fits to the extinction profiles favor Mg-rich over Fe-rich silicates (Min et al., 2007; Poteet et al., 2015).

This census is demonstrably incomplete. Notably, silicates alone are unable to account for the entirety of either the inferred solid phase O or Fe abundances (Jenkins, 2009). The remainder of the Fe could be in iron oxides or in metallic form (Cox, 1990; Draine & Hensley, 2013). The unaccounted O is less readily explained, with suggestions including H_2O ice mantles on large grains (Jenkins, 2009; Poteet et al., 2015).

Silicate and carbonaceous materials may have different origins. Solid grains can condense out of the metal-rich winds from AGB stars. If the star is C-rich, then all of the O is bound in CO and the leftover C forms carbonaceous dust. If the star is O-rich, then all of the C is bound in CO and the leftover O forms silicate dust. It is unclear if this dichotomy persists in the ISM, where grains are destroyed by shocks and regrow on relatively short timescales.

Dust models, on the basis of the spectroscopy and the distinct origins, have generally adopted a multi-component dust paradigm, with the carbonaceous and silicate materials segregated into distinct populations. These include silicate + graphite + PAH models (Draine & Lee, 1984; Zubko et al., 2004; Draine & Li, 2007) and silicate + amorphous carbon + PAH models (Zubko et al., 2004; Compiègne et al., 2011; Guillet et al., 2018).

The principal question we would like to answer is: are all of these materials present on the same grains, i.e., does dust have a single characteristic homogeneous composition, or are these materials indeed segregated into separate grain populations?

The answer to this question has important consequences both for interstellar physics and also for modeling of dust foregrounds in Cosmic Microwave Background (CMB) experiments. For instance, photoelectric heating, chemical catalysis (e.g., of H_2 and of organic molecules), and grain coagulation all depend on the specifics of grain composition. Constraining the homogeneity of the grain population directly informs the lifecycle of metals from their production in stars, to their processing in the diffuse interstellar medium (ISM), to their dynamics in protoplanetary disks.

Dust foreground modeling is likewise very sensitive to the number of independent grain species. Having multiple distinct dust populations each with its own characteristic temperature and far-infrared opacity law compounds the difficulty of effectively parameterizing and accurately subtracting the dust emission (Kogut & Fixsen, 2016; Remazeilles et al., 2016; Hensley & Bull, 2018). The presence of metallic Fe can be a particularly pernicious foreground for CMB science (Hensley & Bull, 2018). If the relative abundances of the various dust components varies across the sky, this would increase the spatial variability of the polarized dust SED and thus amplify "frequency decorrelation." Frequency decorrelation has been identified as a major hurdle for many component separation methods (Tassis & Pavlidou, 2015; BICEP2 Collaboration et al., 2018). Thus, constraining the number of independent dust species directly informs component separation strategies.

In this white paper, we make the case that far-infrared polarimetry can provide a sensitive test of the multi-component dust paradigm.

2 Polarimetry as a Probe of Dust Composition

Rapidly rotating, aspherical dust grains are preferentially oriented with their short axes parallel to the local magnetic field. Thus, the starlight absorbed and scattered by dust and the infrared emission from the dust will be polarized. The alignment efficiency and intrinsic polarization fraction of dust depends upon its composition, and so spectropolarimetry of the dust extinction features has enabled tests of the polarizing ability of the grains bearing silicate and carbonaceous materials.

The silicate features have been robustly detected in polarization (Dyck et al., 1973; Smith et al., 2000), indicating that the silicate-bearing grains are preferentially aligned with the interstellar magnetic field. In contrast, the 3.4 μm feature from aliphatic CH has *not* been detected in polarization, even along sightlines with robust detections of polarization in the 9.7 μm silicate feature (Chiar et al., 2006; Mason et al., 2007).

The discrepancy between the robust polarization in the silicate features and the lack of polarization in the 3.4 μm feature suggests that the silicate and aliphatic hydrocarbon materials cannot be located on the same grains (Chiar et al., 2006; Mason et al., 2007; Li et al., 2014). Thus, these observations support the presence of separate silicate and carbonaceous grain populations.

If there are indeed two distinct grain species with different material properties, and thus different temperatures and FIR opacity laws, then the two components may be able to be disentangled by modeling the FIR dust emission in total intensity. However, the evidence to date is mixed. On the one hand, it has been demonstrated that a single dust component is able to provide an adequate fit to the dust emission observed by *Planck* (Planck Collaboration X, 2016) and even to FIR SEDs constructed from IRAS and *Planck* data (Planck Collaboration XI, 2014). On the other hand, explicit tests of one vs two component dust models have shown a statistically significant preference for two components, first from the FIRAS data (Finkbeiner et al., 1999) and most recently from analysis of the *Planck* data (Meisner & Finkbeiner, 2014). Additionally, a blind component separation has found evidence for two distinct dust components (Zheng et al., 2017).

Recently, far-infrared polarimetry has begun to tell yet a different story. Sensitive submillimeter-millimeter observations of the polarized Galactic dust emission by the *Planck* satellite have revealed little difference in the total and polarized dust SEDs (Planck Collaboration Int. XXII, 2015; Planck Collaboration XI, 2018), suggesting that there is no material distinction between the aligned dust component and all of the dust. BLAST-Pol observations of a translucent molecular cloud in the Vela region extend this conclusion to higher frequencies–the polarization fraction of the dust emission appears flat to within 10% from 250 μm to millimeter wavelengths (Ashton et al., 2018).

To reconcile these threads and elucidate the true nature of interstellar dust, sensitive FIR polarimetry of the diffuse ISM is needed.

3 The Case for Far-Infrared Polarimetry

If there are multiple distinct dust species emitting at FIR wavelengths, each with their own emission law and temperature, then it is in principle possible to disentangle their contributions and compare their inferred properties to physical models and laboratory data. This has not yet been achieved despite good wavelength coverage of the FIR dust SED.

However, polarimetry has several distinct advantages over total intensity. First is the lack of contaminating emission. Both the Cosmic Infrared Background and the Zodiacal Light are important components to the total FIR-submillimeter emission, complicating the component separation problem significantly. Indeed, extragalactic signals presumably from CIB contamination have been found in various extinction maps derived from fits to FIR data (Chiang & Ménard, 2019). In polarized intensity the component separation is much cleaner as Galactic dust is expected to dominate over these other sources.

Second, the distinctions between various dust components that exist in total intensity may be magnified in polarization. For instance, if it is indeed the case that both silicate grains and carbonaceous grains contribute to the total intensity but only the silicate grains produce polarized emission, then the polarization fraction of the emission should change dramatically from the wavelengths where the carbonaceous grains dominate to wavelengths where the silicate grains dominate (e.g., Draine & Fraisse, 2009; Guillet et al., 2018). Such a signal would be most pronounced at high frequencies where the SEDs have a non-linear temperature dependence.

Finally, the polarized emission itself carries information about the grain composition. For instance, magnetic dipole emission from ferromagnetic materials is polarized orthogonally to typical electric dipole emission (Draine & Hensley, 2013). Thus, a decrease in the polarization fraction at millimeter wavelengths or even a flip of the polarization angle would be a distinctive fingerprint of magnetic materials as a component of interstellar dust. Further, the magnetic susceptibility of grains is closely linked to their ability to align with the local magnetic field. Thus, determinations of the polarization fractions of various dust components will help place constraints on their magnetic character (Lazarian & Hoang, 2018).

Polarimetric observations of diffuse sightlines can benefit studies of the much more dense sightlines through star forming molecular clouds. Molecular cloud sightlines can span a wide range of column densities and radiative environments, and thus regions of different dust temperature and grain alignment efficiency. Sub-arcminute measurements of dust polarization are increasingly being used as a probe of the magnetic field geometry in star-forming clouds (e.g., Fissel et al., 2016; Chuss et al., 2019), providing new tests of the role of magnetic fields in regulating star formation and characterizing interstellar turbulence across scales. Disentangling line of sight effects from those of grain composition when interpreting these polarization spectra would be greatly facilitated by comparisons to diffuse sightlines.

4 Recommendations

Observations of polarized dust emission are an important window into the material composition of interstellar grains, and new data will enable definitive tests of dust modeling paradigms that remain unsettled despite decades of effort. In particular, we recommend in prioritized order:

1. Polarimetry of Galactic dust emission in the diffuse ISM from wavelengths shorter than the 140 μm peak to the current 850 μm maps from *Planck*. High frequency observations near 100 μm are the most sensitive to the presence of multiple grain components. High sensitivity observations are required between 350 and 850 μm to extend the BLAST-Pol observations to truly diffuse sightlines. For these observations, frequency coverage is more critical than angular resolution– 1° resolution already captures much of the variation in dust properties across the sky on diffuse, high-latitude sightlines. Such measurements could be achieved in part by future space-borne CMB missions (e.g., PICO) and FIR missions like SPICA and OST which have polarimetric capabilities. These missions could be complemented by balloon-based observations (e.g., PIPER, PILOT, BLAST-TNG, and successors) to provide requisite coverage at the highest frequencies.

2. Construction of polarized Galactic dust SEDs on single lines of sight at frequencies lower than 353 GHz to look for variations due in particular to magnetic nanoparticles and/or polarized anomalous microwave emission. Much of the analysis of the dust polarization spectrum measured by *Planck* has been done by averaging over large sky areas (e.g., Planck Collaboration Int. XXII, 2015; Planck Collaboration XI, 2018), but higher sensitivity polarization data could overcome this limitation. Such observations could be realized as ground-based and balloon-borne CMB experiments (e.g., BICEP/Keck, CLASS, Simons Observatory, CMB-S4, SPIDER, PIPER) push toward map-based component separation and to sightlines nearer the Galactic plane where there is substantial signal-to-noise on dust. Satellites like LiteBIRD and PICO could provide sensitive, full-sky measurements in this frequency range.

3. Finally, we note that these observations would greatly benefit from a concomitant resurgence in mid-infrared polarimetry of the dust spectral features. The best-measured polarization profiles of the silicate features date to the early 1990s (Smith et al., 2000), while the non-detection of the 3.4 μm aliphatic CH feature rests primarily on a few sightlines toward the Galactic Center (Adamson et al., 1999; Chiar et al., 2006). Given the opportunity for joint analysis with polarized emission, spectropolarimetry on more sightlines, particularly those like the sightline toward Cyg OB2-12 which seems to typify the diffuse ISM despite high extinction (Whittet, 2015), would yield additional valuable insights into the physical nature of interstellar dust.

References

Adamson, A. J., Whittet, D. C. B., Chrysostomou, A., et al. 1999, ApJ, 512, 224

Ashton, P. C., Ade, P. A. R., Angilè, F. E., et al. 2018, ApJ, 857, 10

BICEP2 Collaboration, Keck Array Collaboration, Ade, P. A. R., et al. 2018, Physical Review Letters, 121, 221301

Chiang, Y.-K., & Ménard, B. 2019, ApJ, 870, 120

Chiar, J. E., Adamson, A. J., Whittet, D. C. B., et al. 2006, ApJ, 651, 268

Chuss, D. T., Andersson, B.-G., Bally, J., et al. 2019, ApJ, 872, 187

Compiègne, M., Verstraete, L., Jones, A., et al. 2011, A&A, 525, A103

Cox, P. 1990, A&A, 236, L29

Draine, B. T., & Fraisse, A. A. 2009, ApJ, 696, 1

Draine, B. T., & Hensley, B. 2013, ApJ, 765, 159

Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89

Draine, B. T., & Li, A. 2007, ApJ, 657, 810

Dyck, H. M., Capps, R. W., Forrest, W. J., & Gillett, F. C. 1973, ApJ, 183, L99

Finkbeiner, D. P., Davis, M., & Schlegel, D. J. 1999, ApJ, 524, 867

Fissel, L. M., Ade, P. A. R., Angilè, F. E., et al. 2016, ApJ, 824, 134

Guillet, V., Fanciullo, L., Verstraete, L., et al. 2018, A&A, 610, A16

Hensley, B. S., & Bull, P. 2018, ApJ, 853, 127

Jenkins, E. B. 2009, ApJ, 700, 1299

Kogut, A., & Fixsen, D. J. 2016, ApJ, 826, 101

Lazarian, A., & Hoang, T. 2018, arXiv e-prints, arXiv:1810.10686

Li, Q., Liang, S. L., & Li, A. 2014, MNRAS, 440, L56

Mason, R. E., Wright, G. S., Adamson, A., & Pendleton, Y. 2007, ApJ, 656, 798

Meisner, A. M., & Finkbeiner, D. P. 2014, ApJ, 781, 5

Min, M., Waters, L. B. F. M., de Koter, A., et al. 2007, A&A, 462, 667

Planck Collaboration Int. XXII. 2015, A&A, 576, A107

Planck Collaboration X. 2016, A&A, 594, A10

Planck Collaboration XI. 2014, A&A, 571, A11

—. 2018, arXiv e-prints, arXiv:1801.04945

Poteet, C. A., Whittet, D. C. B., & Draine, B. T. 2015, ApJ, 801, 110

Remazeilles, M., Dickinson, C., Eriksen, H. K. K., & Wehus, I. K. 2016, MNRAS, 458, 2032

Smith, C. H., Wright, C. M., Aitken, D. K., Roche, P. F., & Hough, J. H. 2000, MNRAS, 312, 327

Tassis, K., & Pavlidou, V. 2015, MNRAS, 451, L90

Whittet, D. C. B. 2015, ApJ, 811, 110

Zheng, H., Tegmark, M., Dillon, J. S., et al. 2017, MNRAS, 464, 3486

Zubko, V., Dwek, E., & Arendt, R. G. 2004, ApJS, 152, 211