

STATEMENT OF RESEARCH INTERESTS

I am an infrared (IR) astronomer with broad experience including stellar evolution, astromineralogy and dust around evolved stars, galactic chemical evolution, meteoritics and the optical properties of materials. My primary focus is circumstellar dust, which pertains to basic questions of galactic processes and the origin of interstellar dust. Most of my research involves stardust. Dust is a vital ingredient in many astrophysical environments. It is an essential part of star formation processes, and discoveries related to dust formation also pertain to planet-forming disks. Furthermore, dust contributes to several aspects of interstellar processes including gas heating and the formation of molecules. In addition, because mass-loss from evolved stars is driven by radiation pressure on dust grains, it is intimately linked to the precise nature of the circumstellar dust. Dust needs to be well understood in its own right, if we are to understand its contribution to many aspects of astrophysics. My research is intrinsically multidisciplinary as the study of stardust requires a deep understanding of mineralogy and collaboration with geologists, chemists and mineral physicists in order to fully comprehend the environments and processes involved. Below my research is divided into themes, which are closely interrelated.

ASTROMINERALOGY:

The main thrust of my research is to understand the precise nature (composition, size, crystal structure and shape) of dust grains. I use a multidisciplinary approach to constrain the dust species present around both carbon(C)- and oxygen(O)-rich evolved stars. This work involves a combination of chemistry, mineralogy, isotope geochemistry and physical optics, as well as IR astronomy and stellar evolution and is funded by three National Science Foundation grants (including a NSF CAREER award) and a NASA grant.

Carbon-rich astromineralogy:

The work on C-rich dust has already produced several important results. I have made the first steps in reconciling astronomical observations of silicon carbide (SiC) dust and the samples of such dust found in meteorites by matching the polytypes. However, there are further anomalies which need to be addressed, most notably the large size of the dust grains found in meteorites. The problems of laboratory spectra of SiC, which led to the original misidentification of the SiC polytype forming around C-rich stars, are currently being researched by myself and Prof. Anne Hofmeister (Washington University, St. Louis; WUSTL). We have shown that an enigmatic feature at $\sim 21\mu\text{m}$ in the spectra of post-AGB stars is probably also due a dust species containing Si—C bonds, but the precise nature of the substance is, as yet, unknown. The emergence of this feature demonstrates the processing of the dust grains from the AGB to post-AGB phases. More recent studies of the classic SiC feature at $\sim 11\mu\text{m}$ suggest that, at least for some carbon stars, there is an evolution in the dust formed as the star evolves. There is evidence, both in the spectra of infrared (extreme) carbon stars and in the meteoritic presolar grain record, that dust grain sizes get smaller as stars evolve and mass-loss rates increase (contrary to conventional wisdom). Furthermore, the evolution in dust formation may be metallicity-dependent. My studies of carbon stars have been facilitated by the involvement of both graduate (Adrian Corman, Ph. D.) and undergraduate (Grant Thompson, Kristina Wakeman, Chris Azmeh) students.

Several problems still need to be addressed. SiC is clearly forming around AGB stars and is found as presolar grains in meteorites, but it is not seen in the ISM. Why? Furthermore, the laboratory data that has been used previously for radiative transfer modeling is flawed. Newly

derived optical data (produced in collaboration with Anne Hofmeister and Karly Pitman), have been used to re-run such models (with summer student Ben Vega-Westhof) and the resulting 20,000+ models are currently being investigated (with undergraduate research Chris Azmeh). Furthermore, these models have previously assumed/predicted very small grains. However, large SiC grains are found in meteorites with isotopic compositions indicative of formation around AGB stars. Both observational evidence for these large grains and their formation mechanisms must be sought. Furthermore, since our lab data suggests that the enigmatic “21 μ m” feature associated with C-rich post-AGB objects is due to some sort of Si—C compound, further lab investigations of Si—C materials are needed to fully understand the emergence of this feature.

A recent re-analysis of previous studies of carbon stars using the parameters of the 11 μ m SiC feature has shown that most previous studies are flawed, in large part due to their use of the low-resolution, narrow wavelength coverage of *Infrared Astronomical Satellite* (IRAS) spectrometer data. This study has led to an NSF-funded project to disentangle the (circum)stellar properties that determine the mid-IR spectra of carbon stars. The aim of this project is to investigate the precise nature of dust grains around carbon stars, using an integrated experimental-observational-modeling approach in order to understand dust formation and evolution. In particular we will determine the effect of mass loss, metallicity and C-to-O ratio on dust formation. This forms the basis for Adrian Corman’s thesis project. As part of this project we have acquired observing time on the (very competitive) Gemini North telescope to do spectro-imaging and thus gain spatially-resolved spectra of a few close-by carbon stars. The observations have been made (by collaborator Kevin Volk) and we are currently reducing the data. These observations will test the theories of the evolution of dust formation around carbon stars. Another interesting aspect of carbon stars which has been largely overlooked is the SiC absorption feature. Seven objects are known to exhibit this spectral feature and I have recently discovered three more. A paper presenting these new finds together with radiative transfer models has been submitted to the *Astrophysical Journal*.

Oxygen-rich astromineralogy:

Since the late sixties, when the 10 μ m dust feature was first observed, there has been much interest in the exact nature of the dust around cool evolved stars, the processes by which this dust forms and the structure of the dust shells. One example of my work in this area concerns a dust feature at ~13 μ m which was discovered in the IRAS spectra. Since its discovery, three major candidate species have been advanced and continuously investigated: crystalline alumina (corundum; Al₂O₃), spinel (MgAl₂O₄) and silica (SiO₂). The Masters thesis work of my student Kyle DePew concentrated on radiative transfer modeling of O-rich dust shells, with an emphasis on this 13 μ m feature. We showed that spinel was unlikely to be the carrier of this feature, and that only small concentrations of Al₂O₃ are necessary to explain the observed strength of the feature. However, spectroscopy without spatial resolution cannot distinguish between alumina and silica as the true carrier of the 13 μ m feature. It is necessary to determine which features occur in the same spatial region, to show that they arise from the same dust species.

If the carrier of the 13 μ m feature is SiO₂, then there will be a spatial correlation between the emission at 13 μ m and that at 10 μ m, since the laboratory spectrum of silica shows both these features. If there is no spatial correlation between the 10 and 13 μ m features, then the carrier is definitely not SiO₂. If the carrier of the 13 μ m feature is alumina, then there does not need to be a spatial correlation with the 10 μ m feature. Furthermore, alumina is a high temperature condensate which can form closer to the star than silicates or silica. Therefore, we would expect to see the

signature of alumina closer to the central star. Moreover, with increasing distance from the central star, alumina is expected to become coated with a mantle of the (much more abundant) silicate minerals, thus hiding its spectral features. Therefore, if the alumina carries the $13\mu\text{m}$ feature, we would expect this feature to be confined to the region of the CDE closest to the central star. Moreover, if SiO_2 is the carrier of the feature it implies that thermodynamic equilibrium is not attained. Other residual oxides such as MgO , FeO (and Fe_2O_3) should also persist since they have not combined with SiO_2 to form silicates. Therefore, spectra with the proposed SiO_2 feature should also exhibit the features of the other metal oxides. In conjunction with undergraduate researcher, Caleb Wheeler, I am currently undertaking radiative transfer modeling using the optical constants of the residual oxides to determine whether the observed spectra can accommodate their presence. Preliminary studies suggest that these materials need to be present to explain some of the observed features. In addition, our understanding of the underlying silicate/oxide mineralogy remains poor and is currently the subject of a complementary radiative transfer modeling project (with undergraduate Anthony Smith). I also plan to submit a Gemini proposal to do spectro-imaging and thus gain spatially-resolved spectra of a few close-by stars in order to determine the relative locations of the spectral features.

In addition to the $13\mu\text{m}$ feature studies I am also investigating the mid-infrared spectra of red supergiants. A “broad” feature which peaks at $\sim 10.5\mu\text{m}$ has been observed. However, it has been suggested that the “broad” feature is also due to silicate, but that SiO absorption of the short wavelength side of the classic silicate feature shifts the peak of the apparent feature to longer wavelengths. Searching the ISO/IRAS archives for red supergiants, and comparing the spectra over a larger wavelength range, will allow us to resolve this problem. Such an approach may also uncover other correlations/differences between the spectra of similar stars. This study will then be applied to understand a similar spectral feature observed in active galactic nuclei.

My recent discovery of a strong crystalline absorption feature in the IRAS LRS spectrum of an obscured O-rich AGB star has led to a new multidisciplinary project involving a geologist (Alan Whittington) with expertise in the thermodynamics and production of silicate glass. This project aims to test competing theories for (both crystalline and amorphous silicate) dust formation around AGB stars by a combination of observational, theoretical and laboratory studies. With the capability to produce glasses and test the ease of crystallization in Dr. Whittington’s lab, we will be able to determine the conditions under which different types of dust formation occur.

All of the above astromineralogical studies are funded by three NSF grants (including a NSF CAREER award.)

Intermediate mass stars in the Magellanic Clouds:

Evolved stars in the Large and Small Magellanic Clouds (LMC and SMC respectively) are effectively at the same known, respective distances which removes a great deal of uncertainty inherent in studies of Galactic objects. Furthermore, the LMC and SMC have different metallicities (i.e. the abundances of elements more massive than Helium are different). Therefore, the study of AGB stars in the LMC and SMC offers a unique opportunity to assess the relative effects of density, chemistry and metallicity on dust formation processes. I am currently investigating the mineralogy of dust around evolved stars in the Magellanic Clouds with a view to constraining dust formation processes and ISM enrichment as well as the nature of dust that eventually goes into new planetary systems. Constraints on dust formation mechanisms will aid our understanding of processes in the early solar system, when dust formation was the first step

to building planets. The spectra have been classified according to the morphology of the observed IR spectral features and their derived mineralogies. We found a sequence in this classification scheme similar to that seen for the Milky Way evolved stars. This sequence was then correlated with previously determined mass-loss rates for these evolved stars in order to assess the effect of density on the circumstellar shell on dust formation processes (with postdoc Catharinus Dijkstra). Further work on this project includes comparing the mineralogical sequence with the positions of these stars in color-color and color-magnitude diagrams in order to assess the effect of chemistry in the circumstellar shells on dust formation. We plan to compare the results of these studies for the LMC and SMC as well as with Milky Way objects, to determine to effect of metallicity on dust formation processes.

I am currently involved in a couple of Spitzer projects to analyze IRS spectroscopic data of evolved stars in the LMC and SMC in collaboration with Ciska Kemper (University of Manchester), Margaret Meixner (STScI) and the SAGE team. One notable result is the suggestion that the metallicity significantly affects the evolution of dust formation around evolved stars. The Magellanic Cloud projects are funded by a NASA ADP grant # ADP02-0000-0049(PI: Angela Speck) and the UM Research Board (PI: Angela Speck). This project is also a small part of a current Spitzer Legacy program which received 235 hours of observing time to do spectroscopy of dust in the LMC, and has associated funding.

PLANETARY NEBULAE (PNE):

Further along the evolutionary path of intermediate-mass stars are the planetary nebulae (PNe), where the central star has shrunk to a white dwarf and the circumstellar envelope is drifting away from the star. The central star is hot enough to ionize the surrounding medium. This harsh environment leads to a nebula with an onion-layer structure in which the material closest to the central star is most ionized, while the outermost layers are comprised of dust and molecules. Understanding the spatial distribution of the different species and ionization levels enables a detailed analysis of the physical and chemical conditions during the post-AGB phase and how these stars contribute to galactic chemical enrichment.

Optically thick knots appear to be common, if not ubiquitous, in PNe. In addition, I have shown that these knots contain molecular hydrogen (H_2). Furthermore, there is a progression in the appearance of these knots that correlates both with the age (evolutionary status) of the nebulae and, in the case of the Helix Nebula, with distance from the central star. A currently funded Hubble Space Telescope (HST) archive project is studying the relative morphologies of the molecular and ionized gas in a number of PNe observed using both visible and near-IR narrow band images (which trace the ionized and molecular gas respectively). This project has supported two graduate students (Sarah Eyermann and Josh Tartar) and has provided an opportunity for hands on observing experience to PhD student Menzi Mchunu. We are studying the morphology and evolution of the molecular gas in PNe and their contribution to the enrichment of the ISM. The origin of these knots is still unknown, although there have been several suggested formation mechanisms which fall into two main scenarios: (1) they form in the stellar wind during the AGB phase; or (2) they form as a result of the fragmentation of a swept-up shell during the PN phase. It is also not clear whether the knots will survive the PN phase and return molecular gas to the ISM, or they will be completely ionized and dissipate as the PN evolves. An understanding of the process of molecular knot formation and evolution is vital to our understanding of the material return to the ISM during the death throes of intermediate mass stars. In collaboration with Mikako Matsuura (NOAJ), I am supplementing these global studies

of H₂ knots in PNe, with a multiwavelength study of individual knots in the Helix and Dumbbell nebulae, using the Very Large Telescope and Subaru observations, in order to determine their structures and excitation mechanisms.

In addition to the molecular hydrogen studies, I have recently started a collaboration with Prof. R. Henry at the University of Oklahoma to resolve the apparent sulfur anomaly in PNe abundance measurements.

EXPERIMENTAL ASTROPHYSICS:

I have an ongoing collaboration with Prof. Anne Hofmeister at WUSTL. Our aim is to produce a comprehensive database of spectra and complex refractive indices for various crystalline and amorphous silicates and oxides expected to form around O-rich stars, and to understand fully the effects of grain size and impurities on the spectra. This will further constrain the types of dust species around evolved stars, in interstellar dust, protostars, protoplanetary systems, and comets. I plan to compare the dust types in these different regions to determine their chemical and structural evolution. This project is very timely given the unexpected result from ISO that many objects have spectral features associated with crystalline silicates. Furthermore, with the data emanating from the Spitzer Space telescope, and that expected from future IR mission (such as SOFIA or Herschel), even more diverse dusty environments are being observed, and more astronomical IR spectra will need to be interpreted. We are beginning to provide optical data appropriate for these environments, which are currently lacking. This project has been funded in part by NASA. Recent results include disproving the attribution of a carbon star feature to silicon nitride; and a detailed compositional series of spectra for crystalline olivines that will aid in our interpretation of apparent shifts in observed spectral features. In addition, new optical constants for silicon carbide will soon be available and will further the studies of carbon stars. We have a publicly available database of laboratory spectra and refractive indices (<http://galena.wustl.edu/~dustspec/idals.html>).

In addition to the laboratory spectroscopic study, I have started a new collaboration with MU geologist Alan Whittington to produce appropriate amorphous silicate samples for spectroscopic study. This work is funded by a newly awarded NSF grant.

ASTRONOMY EDUCATION:

In addition to my pure research projects, I am involved in astronomy education research. Together with a doctoral student, I have been developing teaching tools specifically for astronomy. In particular we have produced a computer-based laboratory exercise on observing stars that has been presented “Cosmos in the Classroom” meeting (Pomona, CA, August 2007) and will be presented at AAS 211 in Austin, TX. We have also been testing the impact on learning of existing software; designing exercises in 3-d environments to aid in understanding of astronomical concepts; and developing 3-d animations for use in higher level classes, where instruction on interesting astronomical phenomena would benefit from such materials (e.g. seasons on Uranus; relative orbits of the rings of Saturn; lunar libration). We were recently awarded a NSF CCLI grant to develop a proof-of-concept unit to determine whether missions in a 3-D virtual reality environment would improve learning in astronomy.