

Angela Speck - Research Statement

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. I have experience with data reduction for space-based telescopes from working with ISO and Spitzer data. My primary focus is circumstellar dust, which pertains to basic questions of galactic processes and the origin of interstellar dust. Below my research is divided into themes, which are closely interrelated. Numbers below refer to my publication list (PDFs of publications can be downloaded from <http://stardust.astro.missouri.edu/>).

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.

Extremely extended dust shells - AGB mass loss:

Intermediate mass ($\sim 0.8\text{--}8M_{\odot}$) stars evolve off the main-sequence and eventually become asymptotic giant branch (AGB) stars. During the AGB phase, intensive mass loss leads to the formation of a circumstellar shell of dust and gas which contains newly-formed elements originating from nucleosynthetic processes within these stars. Consequently, AGB stars are major contributors of new elements, dust and gas to the interstellar medium (ISM), from which new stars and planets are born.

The circumstellar dust envelopes (CDEs) around AGB and post-AGB stars are the direct outcome of AGB mass loss, and therefore, a pristine fossil record of this mass loss is imprinted on these shells. Imaging the extended dust emission at far-IR wavelengths can be used to trace the mass-loss histories in these CDEs.

The exact nature of mass loss is not yet well understood, but is believed to be driven by radiation pressure on dust grains. Therefore, the time-dependent changes expected in the luminosity and temperature of a star should be manifested in the radial distribution of the dust. By detecting density variation imprinted on the CDEs we can address whether such variations are related to time-dependent stellar properties. Furthermore, while AGB mass loss appears to be mostly spherically symmetric, many studies suggest that post-AGB stars develop at least some axisymmetric structure by the end of the AGB phase. Planetary nebulae (PNe), the end products of AGB mass-loss, are axisymmetric while the early AGB stars are spherically symmetric. Hence, something must have triggered the first development of the aspherical shell structure prior to the late AGB phase. By looking for asphericity in the 2-dimensional structures of CDEs we can address when this phase begins and therefore achieve a better understanding of its origin.

Using ISOPHOT imaging, I have already shown that two well known post-AGB objects (the Egg nebula and AFGL 618) are surrounded by huge dust shells (radius $> 2pc$). Furthermore, these dust shells show evidence for episodic mass loss on the timescale of AGB thermal pulses [18]. We therefore have an observational method for testing theoretical models of the evolution of intermediate-mass stars.

This project continues with both observational and modeling approaches. ISO observations in the far-IR indicate that the dust is cool ($< 50K$) and appears to be heated by the interstellar radiation field (ISRF) at radii larger than about one parsec. In collaboration with Gillian Knapp (Princeton), and Moshe Elitzur (University of Kentucky), I am currently working on radiative transfer modeling of the thermal emission from discontinuous dust shells heated by both a central source and the ISRF. I am advising a student thesis in which previously unidentified large dust shells are sought in the ISO archive. Furthermore, I have supplemented the archival IR observational data with new observations of AFGL 618 at $350\mu m$ produced using the sub-mm imager SHARCII (at the Caltech Submillimeter Observatory, Hawaii; in collaboration with Darek Lis, Caltech). Preliminary results of both the modeling and the sub-mm observations are included in a submitted manuscript [E].

In addition, I am the PI on a Spitzer Space Telescope Cycle 2 project to image more of these extremely extended dust shells. Our project is entitled "MIPS InfraRed Imaging of AGB Dustshells (MIRIAD): tracing mass-loss histories in the extremely extended circumstellar shells of intermediate mass evolved stars." and was awarded ~ 30 hours of observing time to image four objects at both 70 and $160\mu m$. The MIRIAD team comprises thirteen people including many experts in observation and theory and covering many aspects of stellar evolution and mass loss. To date our observations have yielded 2 peer-reviewed articles [4,6] and led to the discovery of a bow-shock where an

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AGB star (R Hya) is moving through the interstellar medium. The analysis of the Spitzer MIPS images is ongoing. The interesting result of the bow-shock associated with R Hya has resulted in a spin-off project on nature of the emission from the shocked-region.

While our observations are yet to shed light on the development of some axisymmetric structure within CDEs towards the end of the AGB phase, the theoretical work on this problem has yielded some interesting results. In particular, simply by assuming conservation of angular momentum, observed axisymmetric properties can be explained [2]. Now the challenge is to understand why angular momentum is conserved.

Astromineralogy:

In addition to the morphology of dust shells around evolved stars, I am very interested in 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.

Carbon-rich astromineralogy:

The work on C-rich dust has already produced several important results [1, 3, 5, 9, 12, 20, 23, 25, 26]. 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 [23], 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; see [9]). Furthermore, the evolution in dust formation may be metallicity-dependent [3].

Several problems 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), can be used to re-run such models. 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 $\sim 21\mu\text{m}$ 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 $11\mu\text{m}$ 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 IRAS LRS 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. As part of this project we have submitted a Gemini proposal to do spectro-imaging and thus gain spatially-resolved spectra of a few close-by carbon stars. In this way we will test the theories of the evolution of dust formation around carbon stars. An interesting aspect of carbon stars which has been largely overlooked is the SiC absorption feature. Seven objects are known to exhibit this spectral feature [5] and three more have recently been discovered. We are currently modeling all ten objects to gain a better understanding of these enigmatic objects.

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Oxygen-rich astromineralogy:

Since the late sixties, when the $10\mu\text{m}$ 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 $\sim 13\mu\text{m}$ which was discovered in the IRAS LRS spectra. Since its discovery, three major candidate species have been advanced and continuously investigated: crystalline alumina (corundum; Al_2O_3), spinel (MgAl_2O_4) and silica (SiO_2). The Masters thesis work of my student Kyle DePew concentrated on radiative transfer modeling of O-rich dust shells, with an emphasis on this $13\mu\text{m}$ feature. We showed that spinel was unlikely to be the carrier of this feature, and that only small concentrations of Al_2O_3 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 $13\mu\text{m}$ 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 $13\mu\text{m}$ feature is SiO_2 , then there will be a spatial correlation between the emission at $13\mu\text{m}$ and that at $10\mu\text{m}$, since the laboratory spectrum of silica shows both these features. If there is no spatial correlation between the 10 and $13\mu\text{m}$ features, then the carrier is definitely not SiO_2 . If the carrier of the $13\mu\text{m}$ feature is alumina, then there does not need to be a spatial correlation with the $10\mu\text{m}$ 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 [8,19]. 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. 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. I 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.

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. 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 [10]. 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

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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 [3] 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).

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, these knots have been shown to contain molecular hydrogen (H_2 ; e.g. [15,17]). Furthermore, there is a progression in the appearance of these knots that correlates both with the age (evolutionary status; O2002) of the nebulae and, in the case of NGC 7293 (the "Helix" nebula), with distance from the central star [11]. A currently funded HST archive project is studying the relative morphologies of the molecular and ionized gas in a number of PNe observed using both WFPC2 and NICMOS. In addition, in collaboration with Joe Hora (CfA), we have a pending Gemini/NIRI proposal to obtain high resolution H_2 images of three PNe for which the ionized gas morphology (as seen by WFPC2) has been well characterized. In this way we will study 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 H_2 knots in PNe, with a multiwavelength study of individual knots in the Helix nebula, in order to determine their structures and excitation mechanisms.

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>).