Fundamentals of dust formation around evolved stars

1. Science aim/goal
Determine formation and composition of the very first dust seeds and trace dust growth around evolved stars, constraining the dust replenishment of the ISM.

2. (i) Scientific Importance: Interstellar dust has played a crucial part over cosmic time through its role in the chemistry and physics of the interstellar medium (ISM) and star-formation efficiency, and in observations through the interstellar extinction. Its origin is related to the late evolution of stars on the asymptotic giant branch (AGB) and supernovae (SNe). In addition to being the main sources of interstellar dust, outflows from AGB stars and SN explosions enrich the ISM with the elements needed to form new stars and planets. Assessing whether AGB stars can account for the large dust reservoirs present in the early Universe, as is inferred from the spectral energy distribution of high-redshift galaxies and quasars, as well as in local galaxies, depends on their evolutionary properties (e.g. mass loss and nucleosynthesis) in environments of varying metallicity. Although overall dust budgets are reasonably well constrained, the formation processes and detailed composition of AGB dust remain major unknowns.
To characterize the detailed chemical composition of dust around AGB stars and supernova progenitor red supergiants, we need to determine which are the fundamental seeds for dust formation. Observations of the warm gas close to the stars can probe the formation and composition of the first dust seeds and trace the dust growth, constraining the physics of mass loss and the dust replenishment of the ISM by evolved stars. Current models of wind driving, essential to our understanding of the mass-loss process, the evolution of AGB stars, and the ISM enrichment, require grains of certain properties in order to sustain steady outflows. Measuring the depletion of the gas will test whether such dust grains can efficiently form in the regions close to the star. Sample studies will investigate how fundamental properties, such as outflow temperature and density, contribute to the differences in dust formation, composition, and growth. Monitoring studies will enable the characterization of time variability in the dust-formation process.

(ii) Measurements Required: High-sensitivity heterodyne observations of molecular emission and absorption lines at 0.5-2.0THz (150-600μm) will enable the detection of molecular species that could serve as nucleation seeds in the warm circumstellar environment. These are e.g. carbon chains and polycyclic aromatic hydrocarbons (PAHs) in carbon-rich environments and e.g. SiO, SiO_2, MgO, Fe, AlO, Al_2O_3, TiO, TiO_2 in oxygen-rich environments. Observations of H_2O will be of particular interest given its significant role in the chemical networks that lead to seed formation. High spectral resolution observations will resolve the velocity structure in the inner circumstellar environment, close to the stellar atmosphere, where the very first dust seeds are formed. These regions are dominated by a combination of outflow and infall, caused by the oscillatory movements of the stellar atmosphere throughout the stellar pulsation cycle. Ideally, given the time dependence of the chemistry, the species should be monitored in time and combined with high-resolution spectroscopy tracing the atmospheric presence and behavior of these species. This will more conclusively constrain the chemical models and prevent misinterpretation of the physical and chemical processes at hand based on single-epoch observations. Wideband spectral coverage will enable observations of multiple species simultaneously, benefiting the exploration efficiency of the chemical diversity of the targets and the mitigation of (relative) time variability. Additionally, observations of the far-infrared dust features using the High-Resolution Spectrometer will enable detailed studies of dust properties such as temperature and composition, constraining the end products of the dust condensation and growth processes. For nearby sources, the radial stratification of the dust properties will be resolved spatially, providing further constraints on the condensation sequence throughout the outflow.

It is known that the chemical type is important (O-rich, C-rich, mixed chemistry) and expected that the wind density (expansion velocity and mass-loss rate) and stellar pulsation type (regular vs. irregular and magnitude of pulsation) can further significantly influence the chemical processes involved in dust formation and growth. We suggest a volume-limited sample of AGB stars covering a large range in this parameter space, needed to fully understand the fundamental chemical pathways of dust formation and growth. A sample of 150 AGB stars within 750 parsecs would allow statistically significant studies.

(iii) Uniqueness to 10µm to few mm wavelength facility: Only a space-based far-infrared facility with high spectral resolution and high sensitivity can guarantee the detection of the highly excited transitions of gas-phase species, including H_2O, essential to dust nucleation and growth as they are excited only in the warmest layers of stellar outflows, in or close to the stellar atmosphere. The far-infrared observations are essential to trace the effects of depletion from the gas phase.

(iv) Longevity/Durability: Complementary spectroscopic observations with ground-based facilities will trace the same and related species in the stellar atmospheres in optical/near-IR (e.g., VLT/E-ELT) and in the colder, external layers of the outflows (at mm wavelengths, e.g. ALMA). High-angular (polarimetry) observations will locate dust of different compositions and sizes in the circumstellar environment (e.g., VLTI and VLT/SPHERE). Spectroscopic observations with JWST will provide constraints on large molecular clusters, an early stage in the dust-grain formation. Broadband photometry with JWST will give dust properties for larger and more distant samples of stars, allowing a comparative study of the metallicity dependence of dust formation.

3. Figure:

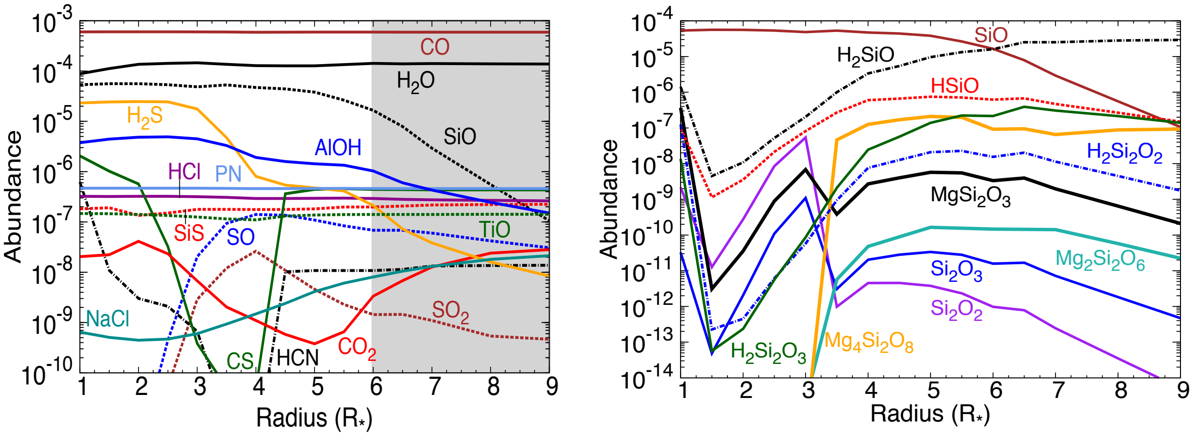

Figure 1: Chemical model results for species essential in the early dust-condensation sequence for oxygen-rich AGB stars. Only heterodyne observations in the far-infrared can probe the highly excited transitions of these species and their intricate velocity structure. The science case aims at covering a large parameter space including a range in densities, chemical types (O-rich, C-rich, mixed), and stellar variability types. ***Left*:** The abundance of simple molecules at different heights above the surface of an AGB star. The grey area indicates the region where the gas has been accelerated away from the star. ***Right*:** The formation of silicate dust clusters out of the simple molecules. Chemical models of this type will be constrained by the proposed observations.

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Name of line(s)		N/A	N/A	Case targets multiple transitions of diverse set of species.
Wavelength/band *Species*	μm/ *GHz*	150-600 *500-2000*	100-750 *400-3000*	
Number of targets		80	150	Broad parameter space essential to science case. Coverage of • chemical types [O-rich, C-rich, mixed] • wind density [v_{exp} ~ 5-50 km/s ; mass-loss rate 10^{-8} - 10^{-4} M_{sun}/yr] • variability types [pulsation strength and type]
Survey area	deg.^{2}	N/A	N/A	Single point targets
Angular resolution	arcsec	5	3	3" will resolve outer dust-growth zone for stars up to 200 pc
Spectral resolution	Δλ/λ	3e-7	2e-7	3e-7 corresponds to 0.1km/s The wind acceleration profile means that at this spectral resolution we can distinguish down to the inner AU of the dust-growth zone.
Full Line Bandwidth	*GHz*	8	8	Dual polarization and sideband-separating (2SB) heterodyne technology combined give 16GHz spectral coverage (2sb x 8 GHz), and 32 GHz overall output (2pol x 2sb x 8 GHz). This results in efficient spectral scan-

				ning and mitigation of time-dependent effects.
Continuum Sensitivity (1 σ)	μJy	N/A	N/A	--
Spectral line sensitivity (1 σ)	W m-2 *K*	$1.0x10^{-21}$	$2.0x10^{-22}$	σ = 0.1Jy in 0.3km/s @ 1THz = $1.0x10^{-21}$ W/m^2
Signal-to-noise		(3)	(15)	Large range over different measured transitions and species.
Dynamic range		1e5 σ	1e6 σ	Observe both weak features and strong emission (e.g. CO) simultaneously.
Field of Regard				Sources spread over full RA/DEC range
Cadence (*observable sky during mission)*		N/A	N/A	
Any other requirement				
Heterodyne Rx specific questions:				
Required Tuning range (Doppler shift)	*km/s*			
Dual frequency requirement?		*NO*	*YES*	*Dual frequency could benefit variability studies, but is not a strict requirement for the science case*
Polarization Normally we will observe one linear polarization, does the orientation matter for your science?		*NO*	*YES*	*Polarization is not an OST requirement for our case. Info can be obtained from e.g. ALMA*
Polarization measurements required?		*NO*		
Off position requirements: *Fixed throw,* *or dedicated off?*				*Dedicated off could be required for sources in the galactic plane. However, most relevant species not excited in ISM, hence fixed throw might suffice also for these.*
if fixed throw, minimum distance				*10arcmin (in declination)*

5. Key references: Bladh et al. (A&A 575, A105, 2015); Gobrecht et al. (A&A 585, A6, 2016); Schneider et al. (Why galaxies care about AGB stars: A closer look in space and time, ASPCS, vol. 497, 369, 2015)

6. Overall topic: Charting the Rise of Metals, Dust, and the First Galaxies