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SYNERGIES BETWEEN VLTI/MATISSE AND ALMA: THE ATOMIUM LARGE PROGRAM

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Abstract. Cool evolved stars are important contributors to the chemical enrichment of the interstellar medium. Within their important stellar winds (10^{-8} to $10^{-4}\,M_\odot\,yr^{-1}$), complex molecules and dust grains are build that represents pristine building blocks for future stellar and planetary systems. The mechanisms behind the mass loss are only partially understood, yielding to the overall mass loss process being modeled as an empirical prescription in most evolutionary models. We are engaged in a multi-wavelength approach aiming at providing a consistent view of the circumstellar environment of cool evolved stars. The accepted ALMA large program Atomium is at the center of this project. It is supported by optical observations, particularly with the new VLTI/MATISSE instrument. We present here the synergies between the radio and mid-infrared interferometric observations.

Keywords: stars: AGB and post-AGB, supergiants, stars: mass loss, circumstellar matter, techniques: high angular resolution, techniques: interferometric

1 Introduction

The winds of Asymptotic Giant Branch (AGB) and Red Supergiant (RSG) stars are key chemical laboratories in which more than 80 molecules and 15 dust species have been detected thus far (Höfner & Olofsson 2018). Through their winds, they contribute $\sim 85\%$ of gas and $\sim 35\%$ of dust to the total enrichment of the ISM (Tielens 2005), and therefore are the dominant suppliers of building blocks of interstellar material. In the wind, a large variety of chemical reactions occur, including unimolecular, 2- and 3-body reactions, cluster growth and grain formation. Hoyle & Wickramasinghe (1962) were the first to propose that the wind acceleration in AGB stars is caused by radiation pressure on newly formed dust grains. Molecules carry the analogous potential to launch a RSG wind, with grains taking over farther out in the wind (Gustafsson & Plez 1992). The prevailing streamlines in these winds are radial, although recent ALMA observations have added structural complexities to this picture (e.g. Maercker et al. 2012 or Homan et al. 2018). We will present here how simultaneous ALMA and MATISSE observations can respectively map gaseous dust precursors and dust grains to better understand the gas/dust transition.

2 The observation programs

2.1 The ATOMIUM large program

Aiming to answer this fundamental question on the gas-dust nucleation process, we have submitted for ALMA Cycle 6 a Large Program (Atomium, ALMA Tracing the Origins of Molecules forming dUst in oxygen-rich M-type stars) focusing on oxygen-rich (O-rich) stellar winds. The Atomium project was approved (113.2 hr), being as such the first ALMA Large Program in the field of stellar evolution. ALMA gives us the unique

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ability to study the gaseous dust precursors in O-rich winds - the many oxides and hydroxides - something we cannot do in carbon-rich (C/O > 1) winds where the aromatic molecules and PAHs that likely grow into carbonaceous grains cannot be observed with ALMA. In addition, the abundances of the most chemically active species in M-type AGB and RSG stars are closer to the average Galactic ('cosmic') abundances. However, some crucial pieces of information are missing from the ALMA data, being the locus of the dust formation, the dust composition, the size of the dust grains, and the radial distribution of the dust species.

2.2 The optical counterpart to ATOMIUM

Unraveling the gas-dust formation pathways implies mapping the relevant molecular and dust distribution in the close vicinity of stars at a very high spatial resolution. Even more, these mappings should be done almost simultaneously (within $\sim$ 1 week) since recent VLT/SPHERE results prove that the photospheric variability of AGB and RSG stars, and by extension of their dust nucleation properties, has an impact on the dust characteristics of the order of days (Khouri et al. 2016). We obtained VLT/SPHERE (Beuzit et al. 2019) and VLTI/MATISSE (Lopez et al. 2014) Target of Opportunity time in order to observe the ATOMIUM targets with these instruments while ALMA scrutinizes them using one of its largest array configuration. This allows us to probe the same spatial scales at different wavelength domains (Fig. 1).

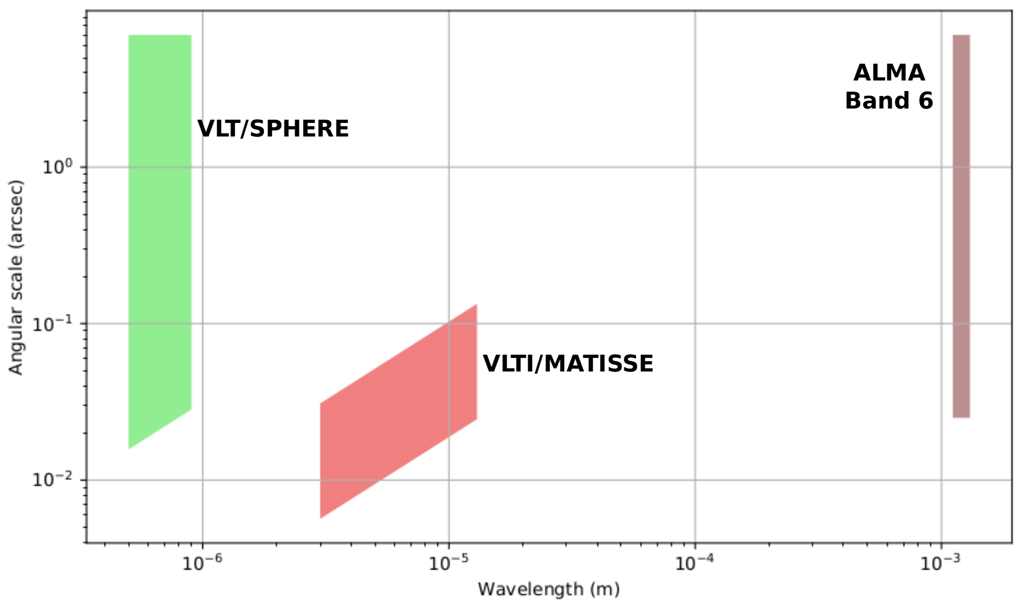

Fig. 1. Wavelength and angular resolution coverage of the ATOMIUM large program and its optical counterparts with VLT and VLTI.

The ZIMPOL visible unit of the VLT/SPHERE instrument provides detailed maps of the linear polarization degree yielding dust scattering locations and inferred dust grain sizes. The high angular resolution of VLTI/MATISSE in the mid-infrared reveals the dust composition, and the radial distribution of dust species (like e.g. Al_2O_3) and gaseous dust precursors very close to the stellar surface. Comparison between these dust density distributions and the gas density distribution retrieved from our ALMA data will pinpoint the location of the dust nucleation sites, the fraction of gaseous dust precursors that condensed into grains, the gas-to-dust mass ratio, and the dynamical behavior starting from the stellar atmosphere throughout the wind acceleration zone.

3 A simulation: the L_2 Puppis system

The acquisition of the VLT/SPHERE and VLTI/MATISSE data is scheduled from June to August 2019, when ALMA will be in its largest array configuration. Therefore, we present here how MATISSE can pinpoint the dust location using the nearby AGB star L_2 Pup as a test-case.

L_2 Pup is an O-rich AGB star located at 64 pc and surrounded by a dusty disk seen with VLT/NACO observations (Kervella et al. 2014). This circumstellar disk is caused by the mass loss of the star and its shaping by a companion first detected by Kervella et al. (2015) with VLT/SPHERE. Further observations with ALMA (Kervella et al. 2016) have refined the characterization of the system. The primary is an $0.6\,M_\odot$ AGB star, evolved from a $1\,M_\odot$ star on the main sequence. The companion is a $12\pm16\,M_{Jup}$ body. This means that it could be a planet or a brown dwarf. The authors argue that the dust clump hypothesis can be rejected due to the lifetime of the object between the VLT/SPHERE and ALMA observations. These precise mass measurements were obtained from the ALMA observations of the gas disk whose Keplerian behavior allowed to constrain the mass of L_2 Pup A, and from the difference of position between the geometrical center of the system and its photocenter for L_2 Pup B. The outer edge of the gas disk had a sub-Keplerian behavior in the area where it was cohabiting with the dust disk seen in the optical. This has been interpreted as friction on the dust grains. Indeed, the radial pressure from the primary star on the dust grains reduces the local effective gravity, which in turn reduces the orbital velocity.

We see that the geometry of the L_2 Pup system is rather well constrained. We can use it to make a simulation of the Atomium observations with the VLTI/MATISSE instrument in the mid-infrared. We used the radiative transfer code RADMC-3D (Dullemond 2012) in order to produce simulations of the dusty disk around the star. We used the same grid and disk parameters as Kervella et al. (2015). However, we used three different inner radii for the disk: 1.5, 4 and 6 au. After doing the radiative transfer, RADMC-3D uses a ray-tracing algorithm to produce cube images of the system (Fig. 2, top). This image are then used as input for the Aspro2 software to make a simulation of MATISSE observations in the N band. For the purpose of the exercise we used only 1 single point of observation at transit. The resulting squared visibilities are represented as a function of wavelength for each baseline and each inner radius on the bottom part of Fig. 2.

The dust disk appears detected by MATISSE. In particular the $10\,\mu$m silicate features is prominent on the shortest baselines where the presence of the resolved disk creates a drop in the squared visibility for each simulation. Moreover, each simulation provides a different signature in the different baselines. This means that we can pinpoint the dust location around the star. The MATISSE observation alone cannot provide enough geometrical information but by combining the ALMA high angular resolution, the SPHERE visible polarization imaging and the MATISSE velocity, we will be able to constrain the onset of dust condensation around the Atomium targets. The interpretation of the observed data will make use of the 3D radiative transfer codes RADMC-3D and McMax (Min et al. 2009). This will allow us to retrieve key parameters such as the composition and size of the dust grains as well as the density, temperature and location of the dust structures. This will prove essential in better characterizing the processes leading to dust condensation within the AGB winds.

4 Conclusions

The Atomium large program will revolutionize our understanding of the mass loss of O-rich cool evolved stars. It will unravel the phase transition from gas-phase to dust species, pinpoint the chemical pathways, map the morphological structure, and study the interplay between dynamical and chemical phenomena. VLTI/MATISSE observations will play a crucial role in this project. As demonstrated with radiative transfer simulations on the nearby AGB star L_2 Pup, they will provide us with unambiguous dust detection and will constrain the dust condensation locus.

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*`https://fys.kuleuven.be/ster/research-projects/aerosol/atomium/atomium`
†Available at `http://www.jmmc.fr/aspro`
‡Available at `http://www.astropy.org/`

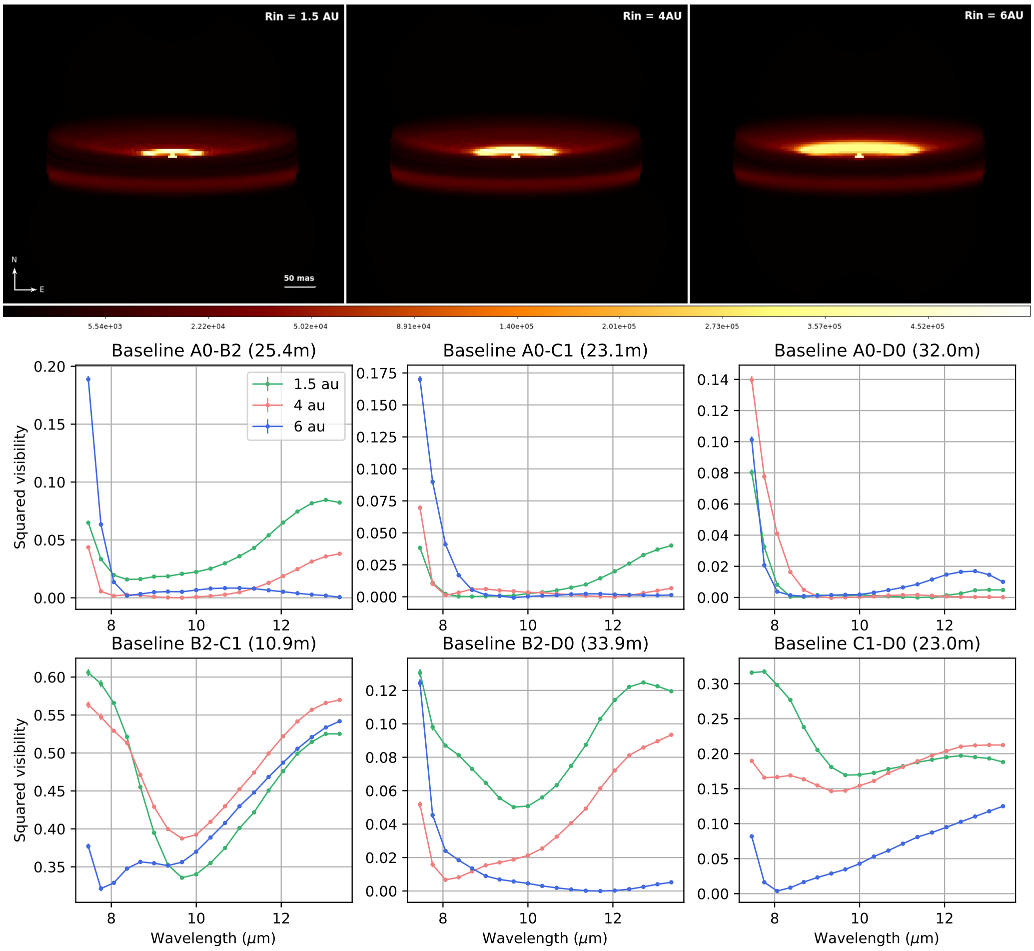

Fig. 2. Top: Simulations of the L_2 Puppis dust disk from the RADMC-3D code. Three different inner radius are used. The image is obtained at 10 μm. **Bottom:** Corresponding VLTI/MATISSE simulations using Aspro.

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