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Variability, Pulsations and Mass Loss of Evolved Stars

INVITED TALK

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Abstract. Evolved low- and intermediate-mass stars that have reached the Asymptotic Giant Branch (AGB) phase tend to show pronounced long-period variability due to large-amplitude pulsations. Those pulsations are considered to play a key role in triggering mass loss through massive dusty winds. The winds enrich the surrounding interstellar medium with newly-produced chemical elements and dust grains, providing building blocks for new generations of stars and planets. Considerable efforts are being made to understand the physics of AGB stars, and to develop quantitative models. This talk gave a brief summary of recent developments, with references to the literature.

Keywords. Stars: AGB and post-AGB, stars: atmospheres, stars: winds, outflows, stars: mass loss, circumstellar matter

1. Introduction

Stellar variability may be caused by various types of physical processes, e.g., surface phenomena which modulate the observed radiation (magnetic or chemical spots, dust clouds, etc.), or periodic variations in luminosity due to pulsations, or structural changes during rapid phases of stellar evolution. Evolved stars that are approaching the end of their lives tend to show combinations of these different phenomena.

Low- and intermediate-mass stars which have reached the asymptotic giant branch (AGB) often show pronounced variability of their luminosities and spectra with periods of about 100–1000 days, brought about by large-amplitude pulsations. The pulsations are presumably a key factor for the heavy mass losses of these objects through dusty winds, with typical mass-loss rates of $10^{-7} - 10^{-5} M_{\odot}/\mathrm{yr}$ and wind velocities of about 5–30 km/s. The pulsations trigger strong radiative shock waves in the stellar atmospheres, intermittently lifting gas to distances where temperatures are low enough to permit dust formation. Radiation pressure on dust grains is commonly assumed to be the driving force behind the slow but massive stellar winds of AGB stars, turning them into white dwarfs and enriching the interstellar medium with newly-produced chemical elements. The mass loss of AGB stars is discussed in some detail in a recent review by Höfner & Olofsson (2018).

2. Variability of AGB Stars: Observations and Models

Observational studies of variability and dynamical processes in cool giants rely mostly on photometric monitoring, but also on high-resolution spectroscopy. The former method can be applied to large samples of stars, even beyond our own Galaxy, owing to the high luminosity of those objects, delivering periods, amplitudes, and their dependence on stellar parameters. High-resolution spectroscopy, on the other hand, is limited to smaller samples, but provides critical quantitative information on atmospheric and wind dynamics via line profiles. In particular, CO vibration-rotation lines at near-IR wavelengths have been used successfully in that context, e.g., Hinkle *et al.* (1982), Scholz & Wood (2000), Nowotny *et al.* (2010); however, profile variability of rotational CO lines in the radio regime have also been detected recently with ALMA by Khouri *et al.* (2016a). The recent progress in high-angular-resolution imaging and spectro-interferometry, spanning wavelengths from the visual to the radio regime, has made it possible to observe evolving dynamical structures directly on the surfaces and in the dusty atmospheres of a few nearby cool giants, and in real time, e.g., Haubois *et al.* (2015), Khouri *et al.* (2016b), Ohnaka *et al.* (2017). Combining such observations with self-consistent models of dynamical processes in the stellar interior (convection, pulsation), the atmosphere (propagating shock waves) and the inner wind region (dust formation, radiative acceleration) is a promising way to understand the fundamental properties of cool giants and their impact on stellar and galactic evolution.

During the last decade, significant progress has been made in identifying period-luminosity sequences found in survey data (such as MACHO or OGLE) with different pulsation modes, using linear non-adiabatic models (see, e.g., Wood (2015), Trabucchi *et al.* (2017), and references therein). Mira stars are most likely fundamental-mode radial pulsators, whereas semi-regular AGB stars are interpreted as pulsating in the first or higher overtones. Improvements in the available data have also led to the discovery of substructures in the period-luminosity sequences, probably caused by non-radial modes. There are, however, open problems, e.g., regarding long secondary periods (see Saio *et al.* 2015), or the pulsation modes of stars with lower luminosity (RGB stars), e.g. Soszynski *et al.* (2007), Mosser *et al.* (2013), Soszyński & Wood (2013), Takayama *et al.* (2013), although the latter problem may be solved by a new interpretation suggested by Trabucchi *et al.* (2017).

Lately, global 3-D radiation-hydrodynamical simulations ('star-in-a-box' models) have been used to study the pulsations of AGB stars. In this case, a parameterisation of convection (e.g., in terms of mixing-length theory), as used in classical linear and non-linear pulsation models, is not necessary because turbulent convective flows develop naturally as an intrinsic part of the models. A preliminary grid of such simulations for AGB stars by Freytag *et al.* (2017) gives first indications of how convection patterns and pulsation properties depend on stellar parameters. The 3-D models demonstrate how long-lasting giant convection cells give rise to variable surface structures and changes in luminosity. In particular, the models presented by Freytag *et al.* show pulsation periods that are in good agreement with the observed period-luminosity relation given by Whitelock *et al.* (2009).

Exploratory 3-D models by Freytag & Höfner (2008) predicted that shock waves triggered by the large-scale convective flows induce complex, variable-density structures in the atmospheres of AGB stars; they leave their imprints on circumstellar dust distributions, since grain growth is sensitive to both prevailing densities and temperatures. Observing visible light scattered by dust grains in the close vicinity of the AGB star W Hya with VLT/SPHERE-ZIMPOL, Ohnaka *et al.* (2016) and Ohnaka *et al.* (2017) recently obtained resolved images of clumpy dust clouds at about $2-3$ stellar radii, which are consistent with structures resulting from large-scale convective flows. An analysis of the observed polarised intensity maps indicates that they trace an optically thin medium with density enhancements of about a factor of 4 in the clouds, and grain radii changing from about $0.1\,\mu$ at minimum light to about $0.5\,\mu$ around the luminosity maximum. Grains of comparable sizes had already been detected in the close vicinity of several AGB stars by Norris *et al.* (2012). These observations support a model of wind-driving by photon scattering on near-transparent silicate grains (low Fe/Mg ratio), as suggested by Höfner (2008). Dynamical atmosphere and winds models based on this driving mechanism also show good agreement with observed visual and near-IR colours, and their variation with pulsation phase; see Bladh *et al.* (2013, 2015) and Höfner *et al.* (2016).

3. Summary and Conclusions

While the variability and atmospheric dynamics of AGB stars have been studied extensively with photometric monitoring and spectroscopy, the recent progress in high-angular-resolution techniques has added a new perspective. Instead of being forced to make assumptions about the structure of unresolved objects when interpreting the data, evolving dynamical patterns on the surfaces and in the dusty atmospheres of the most nearby cool giants can now be observed directly. In order to make a detailed comparison with quantitative models possible and to understand the underlying physical processes, access to time-series of quasi-simultaneous observations from the visual to the radio regime are necessary, tracing the composition and dynamics of molecular gas and dust. The time aspect is even more critical for spatially resolved observations of atmospheres and dust formation zones, which show complex morphologies that change on the time-scales of months, i.e. within a pulsation cycle, and from cycle to cycle.

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