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Mission and ground based facilities for the observations of AGB, super AGB and massive stars

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Abstract. Mass loss from AGB stars and red supergiants plays a key role in the evolution of stars and the chemical enrichment of galaxies. It is a complex process, involving a wealth of physical mechanisms at different spatial scales In this review, I will present how new observing techniques are changing our understanding of this process. We are now able to map the surface of nearby stars, study convection, dust formation and the formation of asymmetries in the ejecta of these giant stars. I will present observational strategies to study the mass-loss process from evolved stars and focus on how high angular resolution observations can help understand the mass loss. As the asymmetries revealed by these observational techniques are very likely due to the presence of binary companions, I will present the newest results on the hunt for binaries t hat started around AGB and RSGs. Finally, I will discuss how bright the future will be, with new observatories and space missions such as the JWST, GAIA, the ELTs, the LSST and new generations of instruments on the 8m-class telescopes.

Key words. Stars: AGBs – Stars: Red Supergiants – Observations: high angular resolution– Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

During the late stages of their evolution, stars enrich the interstellar medium with atoms they formed by nucleosynthesis during their lives. Stellar evolution models are not able to predict when and in which quantities stars will expel this metal-enriched material. Studying the mass loss from evolved stars is thus vital to quantitatively understand the chemical enrichment of galaxies.

Ideally one would like to be able to know how a star from a given mass and metallicity will enrich the interstellar medium. To reach that goal, one need to be able to determine the nucleosynthesis products of this star and determine how these products will reach the surface (via processes such as overshooting or dredge-up). Finally one would need to know when and how the mass-loss process will inject this material to the interstellar medium, via a combination of mechanisms such as convection, pulsation, dust formation and radiation pressure and extra processes such as magnetic fields and binary companions.

During this conference, a lot of discussions occurred about nucleosynthesis, overshooting and dredge-up. This review will thus focus on the mass-loss process, and more particularly on the constraints observations can give to this process.

2. Giant stars: physics at all spatial scales

To understand how giant stars enrich the interstellar medium, one has to study a wealth of physical processes at different spatial scales. Nucleosynthesis occurs in the core of the stars and the freshly produced elements are brought up to the surface via dredge-up. These large stars pulsate and pulsation levitate material and triggers shocks. Behind these shocks, the lifted material is dense and cold enough to condense, so that dust forms. Radiation pressure on the dust grains is thought to trigger the mass loss and gas is carried along via friction.

This wealth of physical processes occurs at different scales, from the core of the star to the interaction between the envelope and the ISM at parsec-scales. This means that to understand the mass-loss mechanism from a giant stars, observations and different wavelengths and angular resolutions are needed. Only nearby stars can be spatially resolved. If we take the Red Supergiant star Betelgeuse as an example, its photosphere has a radius of ~3AU, which at a distance of ~130 pc leads to and angular diameter of ~50 milliarcsec. This can only be probed with interferometrical techniques or using the most recent extreme adaptive optics systems on 10m class telescopes.

The internal envelope (between ~1-10 stellar radii) can be probed by direct imaging with 10m-class telescopes in the optical and in the infrared. While going further away from the star, the gas and dust cool down and it can be probed at longer wavelength in the far infrared and millimeter domains. Such observations of Betelgeuse have been carried out, making it the perfect example to display the variety of physical conditions that can be probed to study the mass-loss process from evolved stars.

Betelgeuse's photosphere was resolved using near-infrared interferometry at the three-telescope interferometer IOTA (Haubois et al. 2009). Two bright spots are detected and are potential signatures of convective cells (Chiavassa et al. 2010). This photosphere was also directly image in the optical with SPHERE/VLT observations (Kervella et al. 2016a), revealing an asymmetric gaseous envelope inside a radius of 2 or 3 times the photosphere. At a similar radius, a dust shell is also resolved. The asymmetries observed tend to confirm that convection plays a key role in levitating the atmosphere of giant stars and triggering the mass loss. Mid-infrared observations with VISIR/VLT revealed the dust formation region, which appear more or less circular, with a high degree of clumpiness for the envelope which also harbours large asymmetries at extension between where the dust is formed and the interstellar medium (Kervella et al. 2011).

Finally, longer wavelengths observations of Betelgeuse lead to a map of the cool dust (Decin et al. 2012), one again pointing at a non homogeneous mass loss. A bow shock also reveal the interaction of the envelope with the interstellar medium. Understanding the mass-loss process from evolved giant stars will thus require a wealth of observations with different techniques.

3. Studying the mass-loss process observationally

As discussed above, a lot of physics is involved in the mass-loss process, making it complex to study observationally. There are certainly many ways to study this process, but I will only list three here.

To really understand the physics of the mass loss, time series observations are the key. Mass loss being a dynamical combination fo different processes, observations over a full pulsation cycle or longer are needed to study the evolution of shocks and dust formation behind the shocks and measure the evolution of the mass-loss rate across the cycle. This can be done for individual nearby stars, for which we can the dust forming region or even the photosphere for the closets ones.

But the risk while doing that is to select stars that are special and thus not representative of the whole family of giant stars or to miss out some classes of stars (like stars with low mass-loss rates). This can be avoided with large samples that can lead to statistical measurements. The best way to do so would be to observe giants in a Galactic volume-limited sample, or in extragalactic samples.

For a Galactic sample, one would ideally want to measure the chemical abundances of the stars through spectroscopy, study its variability due to pulsation with photometry (at different wavelengths) and study its dust composition and dust mass-loss rate via mid-infrared spectroscopy. The gas mass-loss rates can be measured through CO millimetric observations. High angular resolution observation or other binary hunting techniques can also be use to look for companions and see how this affect the gas and dust ejection.

Observations of giant in extragalatic systems can be more difficult (even more for high angular resolution observations), but it can have great advantages. If one observe stars in another galaxy, its distance is usually well known, making the measurements of luminosities and mass-loss rates more accurate (Groenewegen et al. 2007). This also offers the advantage to observe a full galaxy and thus study its dust budget (Matsuura et al. 2009).

As a few talks during this meeting have been focused on extragalactic work, I will focus my review on Galactic work, and more particularly high angular resolution observations.

4. Mass loss through high angular resolution observations

High angular resolution can be very useful to study the dust very close to the star and tackle key question regarding the mass-loss process. This process, thought to be understood for decades, remains far from being fully understood. Susanne Höfner describes it as a two-step mechanism, with first convection and pulsation that levitate the atmosphere and trigger shocks, which leads to the formation of dust. The radiation pressure from the star on the newly formed grain will then accelerate them, so that they can escape the gravitational attraction of the star and carry the gas along via friction. This is the classical view of the mass-loss process, at least for AGB stars.

RSGs and AGBs are similar in many ways, as they are both cool, mass-losing giant evolved stars with winds sharing many similarities. RSGs have larger masses than AGBs, and tend to have lower pulsation amplitudes and smaller convective cells, but more numerous cells. Models predict that the atmospheres of AGB stars are more extended than those of RSGs. Near-infrared interferometric observations have revealed that for AGB and RSG stars, the atmosphere is more extended in the CO and water bands than in the continuum and that the extension of the atmosphere is similar in AGB and RSG stars (Arroyo-Torres et al. 2015). RSGs models can not reproduce this extension, An extra mechanism is thus necessary to explain the mass-loss mechanism of RSGs. This could be radiation pressure on lines (Josselin & Plez 2007).

As shown before, high angular resolution observations can lead to great insights in the mass-loss process from nearby giant stars. New high-angular-resolution instruments such as ALMA, SPHERE/VLT and the VLTI have started a small revolution in the study of the circumstellar environments around these stars.

We can now talk about milliarcsec observations and high angular resolution observations are bringing a revolutionary view of the close environments of AGB and RSG stars, and help us better understand their mass-loss process and the way they interact with binary companions. Optical/infrared interferometry of AGBs and RSGs now offer imaging capabilities, so that we can image convective shells at the surface of giant stars (Haubois et al. 2009). Mid-Infrared observation enable us to map the dust formation (Paladini et al. 2017). Combining interferometry with high spectral resolution, we can map the MOLSPHERE around these stars and study the gas dynamics. This was done for the bright RSG Antares by (Ohnaka et al. 2015), who mapped the star through out a near-infrared CO line at two epochs. This revealed that the atmosphere appears different across the CO line profile, that the velocity field is non homogeneous and that changes occurs within a year. All this is fully consistent with the signature of convective cells.

The work of Woitke (2006) showed that for oxygen-rich AGB stars, the grains that can form are either forming close to the star ad transparent (Mg-rich silicates) or forming far away from the star and opaque. This means that radiation pressure on the grains can not work, due to a lack of opacity of these grains. Another mechanism should be invoked for mass loss from oxygen-rich stars to work.

Hofner (2008) thus suggested that the mass loss from these stars was due to scattering rather than absorption. Large grains are needed for scattering to be efficient.

Extreme adaptive optics observations, combined with polarimetry can enable the determination of the dust distribution and grain size. Ohnaka et al. (2016) obtained spectacular results from SPHERE/VLT observations of the AGB star W Hya. Their polarimetric signal is interpreted as being due to scattering by large dust grains (0.4-0.5 microns). This is consistent with models of mass loss suggesting that the momentum of the dust grains is acquired via scattering rather than absorption. Similar results were obtained with SPHERE/VLT for the RSG star VY CMa (Scicluna et al. 2015) and the AGB R Dor, for which the surface of the star was even resolved (Khouri et al. 2016). The surface of the RSG Betelgeuse was also resolved with SPHERE/VLT (Kervella et al. 2016a), showing the presence of asymmetries likely due to convection and the presence of dust close to the star. All these results indicate that the mass loss from both O-rich AGB and RSG stars is very likely linked to convection and scattering by large dust grains close to the surface of the stars.

5. Asymmetries: binary systems?

If one looks at the latest high angular resolution observations of giant stars, it appears clearly that large asymmetries are observed, e.g. in VY CMa (O'Gorman et al., 2015) and the Fried Egg Nebula (Wallstrom et al. 2015); (Wallstrom et al. 2017). To explain these structure, some extra angular momentum is needed. This momentum could come from a binary companion and/or a magnetic field. Many planetary nebulae harbour such momentum excesses and morphologies. CO observations of proto-planetary nebulae have show that most of these objects have excess momentum that could not be explained by radiation pressure only (Bujarrabal et al. 2001). The latest discoveries in the field of planetary nebulae lead to the conclusion that binaries were playing a key role in bringing the extra momentum needed for the shaping of non spherical Planetary Nebulae (see e.g. Boffin et al. 2012; Jones & Boffin 2017). So, if binaries are common in PNe, there should be some non single AGB stars. Unfortunately, companions are very difficult to directly image around AGB stars, as those stars pulsate and are often embedded in dust, making the hunt for binary companions difficult

One way to look for the presence of binary is via high angular resolution observations. Recent theoretical work by Mohamed & Podsiadlowski (2007) presented a new interaction mechanism between and evolved star and a companion: Wind Roche-lobe overflow. This can lead to the formation of 3D spiral structures. The discovery of such a spiral around the AGB star R Scl quickly became an iconic ALMA image (Maercker et al. 2012). Looking for such spirals is thus a new way to indirectly find binary companions of evolved stars. Such spirals were found with ALMA around Mira (Ramstedt et al. 2014), IRC+10216 (Decin et al. 2015), LL Peg (Kim et al. 2017) and more are being discovered.

The onset of observations with extreme adaptive optics instruments such as SPHERE/VLT are also increasing the number of known spiral structures around evolved star. Spirals have thus been discovered around Pi1 Gru (Lagadec et al, in prep), the post-RSG binary system AFGL 4106 (Janin-Potiron et al., in prep, Lagadec et al. 2011). The spiral around the binary WC+O star WR 104 was also directly imaged for the first time (Soulain et al. 2016). New observations combining extreme adaptive optic observations and infrared interferometry should lead to the localisation of the shocks and dust formation zone, and thus better understand the formation of these spirals production huge amounts of dust (up to $10^{-6} M_{\odot}\ yr^{-1}$).

Binary system can also lead to the formation of jets, for which many mechanisms have been proposed recently (Staff et al. 2015; Chen et al. 2016). Mapping such jets, binary systems and their physical properties is a key to constrain the physical processes responsible for jets. The symbiotic binary system R Aqr is ideal for this purpose. SPHERE/VLT observations lead to spectacular images, for which the binary system is resolved with a precessing jet (Schmid et al. 2017). The binary system is resolved for the first time, with a separation of 40 milliarcsec (8AU). The precessing jet is emerging from the secondary and the orbit of the system is being determined. ALMA observations will enable the study of its dynamics, so that this object should become a benchmark for the physics of jets around evolved stars.

Finally, SPHERE/VLT images of one of the closest AGB stars (L2 Pup) lead to very spectacular images (Kervella et al. 2015). It clear revealed the presence of an equatorial disc, with material being ejected perpendicularly to the plane of the disc. A secondary source was also detected at ~2AU. ALMA observations (Kervella et al. 2016b) revealed that the dynamic of the disc is keplerian, and that the central star has a main sequence mass very similar to the one of the sun. The mass of the detected companion is estimated to be of $\sim 12M_{Jup}$: a planet was thus certainly imaged around an AGB star. Massive planets could thus be important too in shaping evolved stars, as predicted by Soker (1996).

6. Future instrumentation/missions

As described above, new observatories/observing techniques such as ALMA, extreme adaptive optics and optical/IR interferometry have lead to a revolution in our view of the mass-loss mechanisms from evolved stars and the importance of binaries in this process. Future instruments and observatories will certainly continue this revolution.

GAIA will enable a better estimate of the distances, leading to more accurate luminosities and mass-loss rates measurements.

Observations with the JWST will lead to the study of the mass-loss history of individual, resolved, objects by mapping its ejecta. It will also map features that are not observable from the ground and allow the study of dust evolution after the AGB/RSG phase, when the dust is exposed to a harsh radiation field from the hot central star. Extragalactic work will also enable the quantitate measurement of the impact of giant stars to the dust cycle in galaxies.

The LSST will open a new window on time-domain astronomy and give a understanding of pulsation and its impact on mass loss. The new generation of extremely large telescopes will allow the direct imaging of the surface of giant stars, to resolve binaries, study resolved populations and abundances, and bring a better understanding of the impact of giant stars on the chemical evolution of galaxies.

To finish this review, I will put a special emphasis on MATISSE, the new recombiner of the VLTI. It will be able to map dust around evolved stars in the infrared with a resolution down to 3 milliarcsec. MATISSE will get its first light in 2018 and a lot of observing programmes will be devoted to the understanding of mass-loss from evolved stars. Observations of red supergiants/AGBs will enable the mapping of bipolar outflows and the detection of asymmetries in the envelopes. Quantitative measurements of their clumpiness will lead to more accurate measurements of their mass-loss rates. Finally, the exquisite angular resolution it will reach in the infrared will permit the mapping of dust formation and of the different dust species, and revolutionise our view of dust formation.

7. Conclusions

In this review, I have shown that high angular resolution observations are revolutionising the way we see mass loss from evolved stars. We can now map the surface of nearby stars, study convection, dust formation and see how companions can lead to the formation of spiral structures and jets in the ejecta of these giant stars. A planet around an AGB stars was also very likely imaged for the first time, giving insights on the future of our solar system.

The mass-loss process still needs to be better understood, to stellar models and galactic evolution models more accurate.For that, we need to study quantitatively the physical processes such as shocks and dust formation via time-series observations.

Measuring the physical properties (mass-loss rates, binary influence etc.) for a statistically significant sample of AGBs and RSGs will enable a better quantitative understanding of the impact of these stars on on the chemical enrichment of galaxies via the mass-loss process. Currently, high angular resolution observations are focusing on a few spectacular targets, but the whole stellar population needs to be understood. Once such large samples are studies in-depth, we will hopefully be able to reach our main goal: being able to predict the gas and dust mass-loss rate and their evolution for any given stars, knowing only their fundamental parameters (mass, age, binarity, metallicity, etc...).

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