Report on the ESO Workshop

Stellar End Products: The Low-mass – High-mass Connection

held at ESO Headquarters, Garching, Germany, 6–10 July 2015

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There are many similarities in the mass-loss processes between evolved low-mass and high-mass stars and the workshop brought together observers and theoreticians to compare and contrast the asymptotic giant branch and red supergiant evolutionary phases. Asymmetric and collimated mass loss, bipolarity, binarity, stellar rotation and magnetic fields were among the key topics explored. Many results were displayed from state-of-the-art high spatial resolution facilities, such as ALMA and the VLTI. A summary of the workshop topics is presented.

Figure 1. The STEPS attendees photographed in front of the entrance to the Headquarters extension.

The mass loss from cool asymptotic giant branch (AGB) and red supergiant (RSG) stars leads to the formation of planetary nebulae and supernovae, respectively, and puts a large amount of material into the interstellar medium (ISM). Collectively it is therefore an important process for understanding the ecology of a galaxy and the lifecycles of stars of both low and high mass. There have been significant recent advances in both the observations and theory of the late stages of stellar evolution, motivating a workshop to consider the synergies of AGB and RSG evolution. High-resolution facilities, such as the Very Large Telescope Interferometer (VLTI) in the near infrared and the Atacama Large Millimeter/submillimeter Array (ALMA) in submillimetre and millimetre wavebands, and other telescopes such as Hubble Space Telescope, start to resolve scales down to the size of the stars themselves. These new data provide an opportunity to revisit the outstanding questions of late stellar evolution, which formed the core topics of the workshop.

The workshop extended from Monday afternoon to Friday, providing an intense 24 invited review talks, 24 contributed talks and five lively discussion sessions. There were 46 posters, and a special session with on Wednesday afternoon was provided so that the posters could be appreciated and discussed with *Bier und Bretzen*. The 113 participants (see Figure 1) enjoyed extensive snacks and a conference dinner in Garching. We provide a summary of the sessions in chronological order of the meeting. Many of the talks are provided on the workshop web page[1] and copies of many of the posters are also available[2].

Opening reviews

The first afternoon was devoted to overviews of the exploration of AGB and RSG stellar products from the observational side. The workshop was opened by the ESO Director General, Tim de Zeeuw, who emphasised that one of ESO's core missions is to provide scientific coordination and dissemination of scientific results though meetings just like the present workshop. Of course its other mission is to provide observing facilities, and he described the current and future state of the Observatory, with emphasis on the European Extremely Large Telescope, which has now entered the construction phase. The first scientific talk was a grand overview by Albert Zijlstra, in which the important role of mass loss in evolved stars of all masses for the enrichment of the ISM was laid out. The topic of asymmetry of the mass loss at all stages was introduced and was a recurrent theme throughout the meeting. The roles of stellar binarity and rotation in driving the asymmetries of mass-loss nebulae were also introduced and the striking similarity of the spiral CO outflow from the AGB star R Scl mapped by ALMA (Maercker et al., 2012) and the spiralling dust nebula around the Wolf–Rayet (WR) star colliding wind binary WR 140 (Williams et al., 2009) was duly remarked.

Eric Lagadec presented a summary of the closely related meeting to commemorate Oliver Chesneau, entitled "The Physics of Evolved Stars"[3], which was held in Nice in June. The topics of the meeting had many similarities with the workshop, covering Chesneau's work on low- and high-mass stars with particular emphasis on the use of high resolution and interferometry for studying the shapes and surfaces of stars and their immediate environments. One highlight selected by Lagadec was the VLTI PIONIER (Precision Integrated-Optics Near-infrared Imaging ExpeRiment) observations of Antares (α Sco), revealing 16 lobes of the visibility function. The Chesneau Prize Lecture was presented by Julian Milli as part of that meeting.

Hans Olofsson described millimetre/submillimetre and radio observations of the envelopes and photospheres of AGB and RSG stars and the large number of different molecular species (~ 80 in AGB, and

~ 25 in RSG) detected, but with many lines left unidentified (called *U*-lines). Currently the determination of the mass-loss rates is still only good to ~ 50 % despite sophisticated modelling. ALMA will be the key to advances in this field and is already showing interesting results, such as the resolution of the stellar surface of Mira (Vlemmings et al., 2015). Roberta Humphreys then reviewed the evidence for mass loss in RSGs from optical and near-infrared (NIR) observations. Near- and mid-infrared imaging and spectroscopy are now providing increasing detail on the mass loss, revealing it to be episodic and driven by pulsation and convection. The presence of bow shocks and dust concentrations remote from the stellar surface, together with measurements of their radial velocities and proper motions, diagnoses the effects of continuous and episodic mass loss on the nearby environment. The archetype of this category is of course η Car, which has shown several individual many-$M_\odot$ ejections over the last 170 years.

The introductory sessions closed with presentations on the capabilities of ALMA and optical–NIR interferometry. These facilities are particularly well-matched to study the details of the circumstellar, and stellar, regions of AGB and RSG stars. Leonardo Testi described the current state of ALMA and plans for Cycle 4 (including linear polarisation) and Cycle 5 (Band 5 for 163–211 GHz). Only three optical–NIR interferometric instruments now survive from the developments of the 1990s — the Navy Precision Optical Interferometer (NPOI), the Center for High Angular Resolution Astronomy (CHARA) and the VLTI — as reviewed by Jean-Philippe Berger. On the VLTI, the two second-generation instruments, GRAVITY for NIR spectro-imaging and microarcsecond astrometry, and MATISSE (Multi-AperTure mid-Infrared SpectroScopic Experiment) for mid-infrared spectro-imaging, will be commissioned in the next few years. Berger emphasised how, increasingly, image reconstruction will lead to more realistic imaging capabilities, such as with the VLTI's four-telescope beam combiner PIONIER. With its increased efficiency, PIONIER facilitates interferometric surveys. Berger closed by seeking input from the evolved star community for plans for the VLTI in the next decade.

Stellar evolution and atmospheres

The session was opened by Georges Meynet on the physics of massive stars. The challenges are to explain how the observed properties of rotation, magnetic fields and binarity are affected by environment and evolution, and what their influence on the structure of the stellar interiors is. Rotation is an active topic in the research on massive stars and causes mixing, driven by shear or meridional currents; however an efficient transport mechanism for angular momentum still seems to be lacking. Meynet introduced the flux-weighted gravity–luminosity relationship, which is very tight and showed how it demonstrates that the mass-loss rate in RSGs cannot be very high, except at the end of evolution, prior to a supernova explosion. Paola Marigo described modelling of the molecular chemistry of AGB star atmospheres in terms of pulsations, which provide shocks leading to non-equilibrium chemistry. The AGB atmosphere is very dynamic and HCN abundances, for example, can vary through the pulse cycle. Alain Jorisson described a technique for exploring the velocity field within the stellar atmosphere based on a method by Schwarzschild using the cross correction of spectra with masks sampling different line formation depths. Using this method, a full spectrum can be synthesised as a function of T_{eff}, g, M, Z, etc. Applications to the AGB star Mira (ο Ceti) and the RSG star μ Cep based on long-term spectral modelling were described.

Pierre Kervella presented an invited talk on high-resolution observations of RSG atmospheres, concentrating on Betelgeuse and Antares. The VLTI and ALMA have resolved the surface of Betelgeuse (diameter ~ 40 milliarcseconds [mas]) and the few convective cells resolved appear to be nearly as large as the star itself (see Figure 2). SPHERE ZIMPOL (Spectro-Polarimetric High Contrast Exoplanet Research – Zurich Imaging Polarimeter) observations of Betelgeuse in the *V*-band show that it is not round and, in the NIR, an incomplete dust shell with dust plumes is visible. From time-lapse imaging, these dust features show plane-of-sky velocities in the range 10–40 km s^{-1}. Michael Gordon discussed yellow supergiants (YSGs),

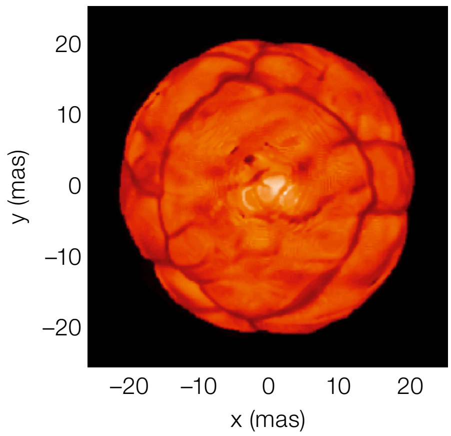

Figure 2. Intensity map of the best-matching snapshot of a radiative hydrodynamics simulation of Betelgeuse at 2.2 μm based on AMBER observations. From Montarges et al. (2014).

caught between excursions between the red and blue at the high luminosity end of the Hertzsprung–Russell (HR) diagram. By searching for such stars in M31 and M33, a sample of 30 YSGs has been found from photometry. Based on extensive and high time resolution observations with CoRoT and Kepler satellite data, Benoit Mosser described the modelling of stellar oscillations. While, in the Sun, pressure (p) waves can account for the asteroseismological data, in RSGs mixed gravity (g) and p waves dominate. Mosser described the seismically enriched HR diagram for subgiants and red giants, where mass as well as L and T_{eff} allows the stellar evolution to be mapped and the late evolutionary stages to be distinguished (Mosser et al., 2014).

In the discussion session, the view was expressed that the in-depth study of individual (quite probably peculiar) stars should be conducted in conjunction with a transition to surveys. On the question of when a supernova (SN) occurred — in the blue or red supergiant phase — it was suggested that the frequency of SN types which will emerge from the many SN surveys underway could be a useful diagnostic.

Mass-loss mechanisms and dust

Susanne Hoefner opened with a theoretical view of the dynamical atmospheres of AGB stars. Stellar pulsations

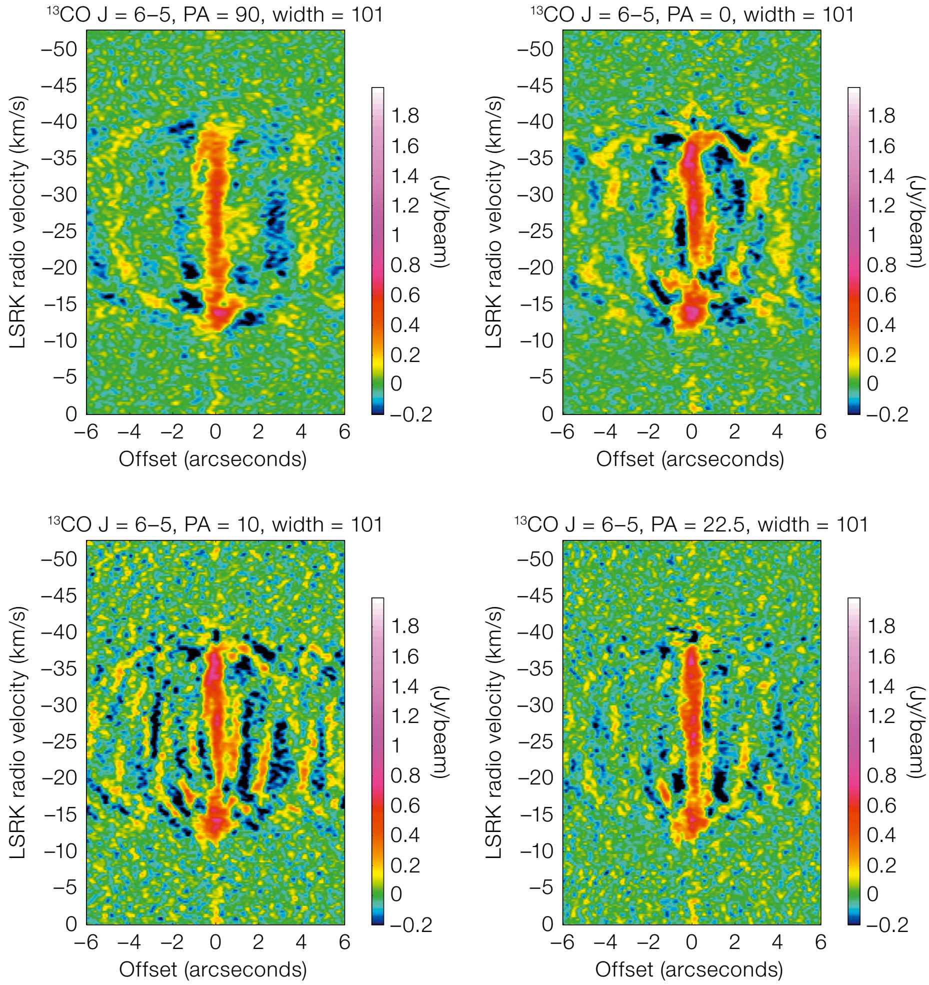

Figure 3. Position–velocity diagrams for CW Leo from ALMA ^{13}CO J = 6–5 emission at 661.067 GHz shown at four position angles of 90, 0, 10 and 25 degrees (indicated). From Decin et al. (2015).

and convection drive shock waves; dust can form in the atmosphere in the wake of these shocks. Radiation pressure on the condensed dust then drives mass loss. The type of the AGB star, M- or C-type, then sets the dust formation as either O or C for that fraction of the matter not locked in CO. The infrared opacity of C grains is featureless, but silicate grains have many features; in O-rich stars the candidate species for driving the mass loss is Mg_2SiO_4. Magnesium silicate grains with sizes in the range 0.1 to 1 μm appear to drive realistic winds in the models. More dust species are being investigated for their role in wind driving, especially for C/O < 1. Sara Bladh showed some of these time-dependent wind models for M-type stars, and how the photometric variations though the pulsation cycle are well matched.

The wind of the O-rich AGB star R Dor was studied by Theo Khouri, who presented impressive SPHERE VISPOL narrow- and broadband images. The wind is modelled by silicates and Al_2O_3. Then ALMA data on the C-rich AGB star CW Leo, a bipolar source, were presented by Ward Homan; this source shows a binary-star-induced spiral, similar to R Scl but with a different viewing angle; see the position–velocity diagrams in Figure 3.

Graham Harper gave a remote presentation from Colorado, which worked faultlessly. He described modelling of the extended atmospheres of RSGs. The primary aim is to measure flows (outflow and turbulence) in the wind acceleration zone of supergiants, such as VV Cep and Betelgeuse. Alfvén-wave-driven outflows are still considered as viable, and observations to detect the 26 μm [Fe II] line in emission to study the circumstellar emission of Betelgeuse and test the magnetohydrodynamic (MHD) models were described. Claudia Paladini presented VLTI observations of AGB stars with a range of instruments, including AMBER and PIONIER, to map the surface features. It appears that AGB stars are not necessarily round, and the circumstellar shell changes shape though the pulsation period, as observed for Mira. Polarimetric imaging of Betelgeuse was presented by Xavier Haubois. The NIR polarimetric observations (Norris et al., 2012) of the thin inner dust shell are complemented by SPHERE ZIMPOL polarimetry. Peter Scicluna showed high-contrast polarimetry observations with SPHERE of the RSG VY CMa with evidence for large (~ 1 μm) grains.

Anita Richards explored the properties of the clumps and asymmetries in the circumstellar environments of mostly O-rich stars. The material is driven, before it condenses to dust, either by shocks in sub-photospheric layers or perhaps by the hottest dust condensing. The dense regions are probed by H_2O 22 GHz maser spots, and, from the number of maser spots, it is suggested that between two and five clouds are produced per stellar period, perhaps originating in spots on the stellar surface. These clumps, but not the masers themselves, probably survive ejection to contribute to the outer shells: in AGB stars the masers only survive a few months, but persist for years in RSGs. Radio continuum studies of extended thermal atmospheres of RSGs were considered by Eamon O'Gorman for Betelgeuse and VY CMa. A typical F_ν slope of $\alpha = 1.3$ is measured, steepening to $\alpha = 2.5$ at longer frequencies, and the temperature, mass and density of the dusty envelope can be determined. Dinesh Shinoy described NIR adaptive optics polarimetry of IRC+10 420 and VY CMa observed with the Large Binocular Telescope (LBT) mid-infrared camera (LMIRCAM) and the polarimeter on the Multi-Mirror Telescope (MMT-Pol). In VY CMa linear polarisation up to 60 % was detected, suggesting optically thick dust scattering.

Lyn Matthews described Jansky Very Large Array (JVLA) observations of some Galactic Cepheid stars to search for evidence of mass loss that could help to explain why the observed and model masses are not in good agreement. The discussion formed a comparison of the mass loss in high- and low-mass stars: it appears that AGB stars are more efficient at producing dust than the higher mass RSGs.

Binaries, shells and shaping

Since it is considered theoretically challenging to understand how single stars can develop strong asymmetries in their mass loss, and especially produce the elaborate morphologies of some planetary nebulae (PNe), such as bipolar, multipolar, jets, etc., formation through binary interactions is a very attractive alternative. Orsola de Marco presented theoretical progress towards explaining the frequency of asymmetrical PNe through binary interactions, and in particular close binary interactions. Roche lobe overflow (RLOF) is considered a promising mechanism and the number of known observed short-period binaries is increasing as long-term monitoring projects probe this domain. Wind RLOF can lead to larger accretion rates than wind accretion and may be able to power the jets observed in some PNe. Three-dimensional hydrodynamical modelling of common envelope binary evolution is underway. The binary star theme was continued by Shazrene Mohamed, but for higher-mass stars, such as Betelgeuse. The results of simulations show that the formation of bow shocks and Rayleigh–Taylor instabilities in the circumstellar media, and the role of binary stars, are central for the creation of tails (such as for Mira), pinwheel nebulae (such as for WR 140) and, of course, for novae.

Michael Hillen showed the first milliarcsecond image of the post-AGB binary star IRAS 08544-4431 taken with PIONIER. ALMA observations of binary AGB stars were presented by Sofia Ramstedt using CO as the main tracer of circumstellar gas and concentrating on sources with well-known binary separations. One of these is Mira, where the combination of ALMA and Atacama Pathfinder Experiment (APEX) covers the compact and extended circumstellar structures: the fast wind from the evolved secondary has blown a hole in the slower primary star wind. A spiral structure, but viewed more end on than for R Scl (or IRC+10 216, Cernicharo et al., 2015), was found for W Aql (also featured in the prize poster by Magdalena Brunner). SPHERE ZIMPOL *V*- and *R*-band polarisation images at a resolution of ~ 17 mas of the low-mass 141-day period binary system L2 Pup were shown by Migeul Montarges (Figure 4). The structure was modelled by a dust disc using the RADMC-3D radiative transfer code; the binary with a separation of 3 au was resolved. L2 Pup is suggested to be the progenitor of a bipolar PN. Another instrumental approach to resolving structures at high resolution, described by Foteini Lykou, is aperture masking using a single telescope, but multiple apertures. Using NACO (Nasmyth Adaptive Optics System and Coude Near Infrared Camera) the central star of R Scl was marginally resolved into a binary. In V Hya, NACO aperture masking shows the structure changing with time.

Henri Boffin showed the observational progress towards resolving discs or binary stars, using a range of facilities from VLT direct images (resolution ~ 0.5 arcseconds), to Hubble Space Telescope or ground-based adaptive optics imaging (to 0.02 arcseconds) to VLTI PIONIER closure phase imaging at 1 mas. A mini survey with PIONIER of symbiotic stars was outlined: for HD 352, a semi-detached binary, a tidally distorted elliptical image of major axis diameter 1.6 mas was modelled. A series of PIONIER observations of the high-mass binary, HR Car, shows the orbital motion over a period of less than one year to a fraction of a mas. Sebastian Ohlmann described modelling of the common envelope phase of binary evolution using the AREPO 3D hydrodynamics code (from W. Springel) for the evolution of the circumstellar structures.

Magnetic fields

Agnes Lebre introduced the field of stellar magnetism from a ten-year harvest of spectropolarimetry. A recent Zeeman survey of single G–K giants by Aurière et al. (2015) shows the most magnetically active stars are concentrated in a strip on the HR diagram associated with the first dredge up and core He-burning phases. Another magnetic strip occurs at the tip of the RGB/AGB, with observed fields at the 1 Gauss level (also covered in the prize poster by Benjamin Tessore); a several Gauss magnetic field has been detected in the Mira star, χ Cyg (Lebre et al., 2014), which also displays a linear polarisation signature, indicating a departure from spherical symmetry at the photosphere. The detection of magnetic fields in AGB stars and PNe was considered by Wouter Vlemmings and whether the focusing of material into jets, as is common in young stellar objects, could occur in these late evolutionary phases. Magnetic fields are detected in masering spots and there is an inverse correlation between spot size and magnetic field, with SiO masers being the most compact and with the highest fields. Extrapolating these fields back to the stellar surface suggests a field ~ 3 Gauss in the case of the Rotten Egg Nebula (OH 231.8+4.2).

Submillimetre polarimetry to determine the alignment of paramagnetic grains in circumstellar envelopes was described by Laurence Sabin, using the Sub-Millimeter Array (SMA) and Combined Array for Research in Millimeter-wave Astronomy (CARMA, now being decommissioned). Linear polarisation of 3–4 % is detected in OH 231.8+4.2, but in the C-rich nebula CRL 618 the peak polarisation was 0.7 %, attributed to the smaller C grains. Alizee Duthu continued the same theme and showed a detection of the magnetic field in the AGB star IRC+10 216 from hyperfine lines of CN, but no detection in the mature C-rich PN NGC 7027. In the discussion on magnetic fields, it was stressed that the MHD models should be linked to radiative models for a consistent treatment. The possibility of bias in selecting binary sources and peculiar/spectacular objects to win telescope time was again raised.

Evolved stars and the cycle of matter

This shorter session, during which the products of late evolution were placed into a galactic perspective, began with Iain McDonald, who considered the amount of matter returned to the ISM

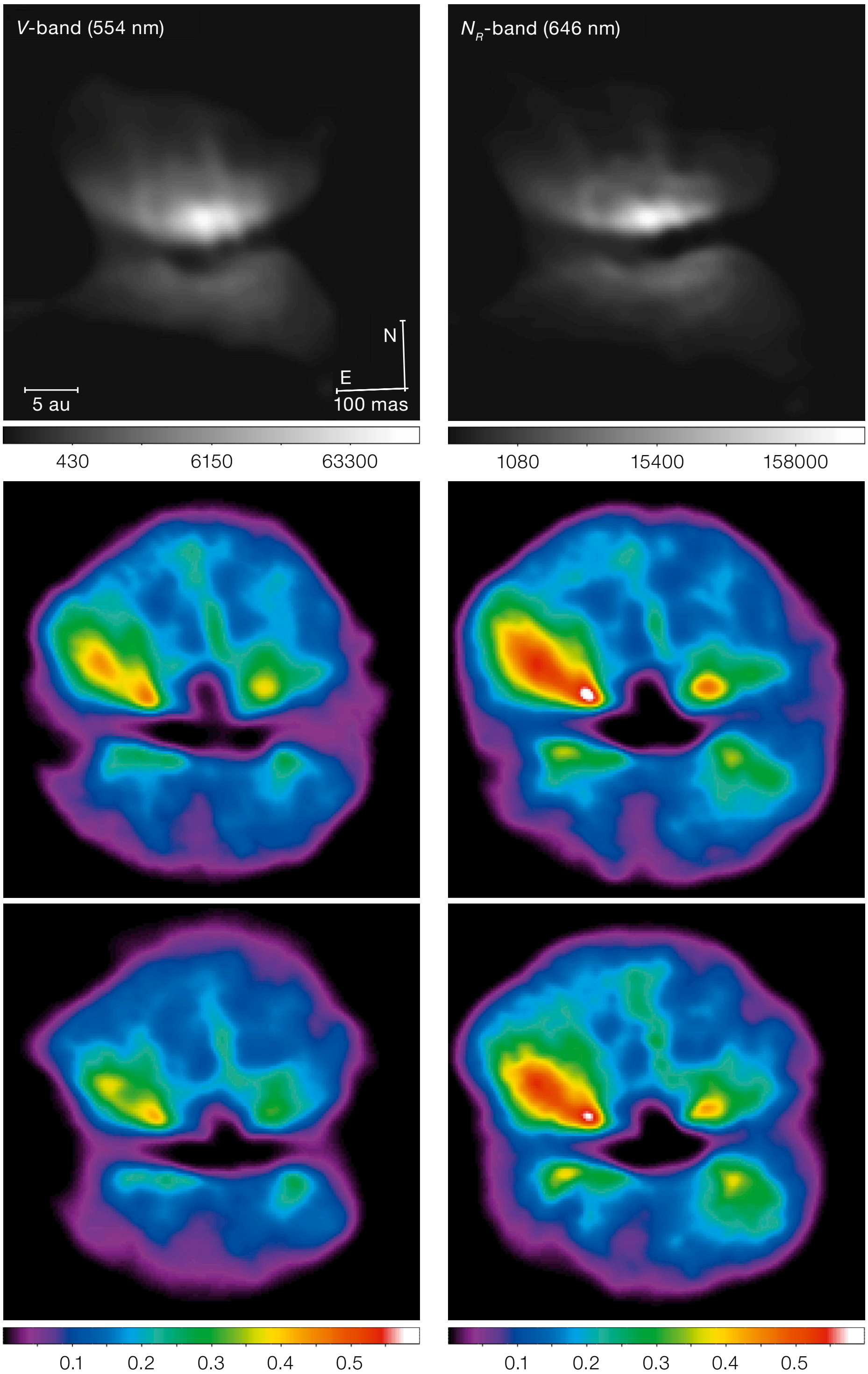

Figure 4. SPHERE ZIMPOL images of L2 Pup in *V*-band (left) and *R*-band (right). Upper: The deconvolved intensity image (log scale); Middle: The linear polarisation from the non-coronagraphic frames; Lower: Linear polarisation from the coronagraphic frames. The field of view is 0.60 by 0.60 arcseconds. From Kervella et al. (2015).

(dust and gas) from the stellar late stages. Mass loss before the onset of dust-driven winds must occur, and even low-metallicity [*Z*] AGB stars need to undergo substantial mass loss (and make dust). Large amplitude pulsations may be an effective source of mass loss before the dust is produced and radiation pressure drives mass expulsion. However the mass-loss rates, velocities and gas-to-dust ratios of AGB stars are still not well known, especially as a function of metallicity and environment, and improved values are required to parameterise the mass return to the ISM, especially pertinent to low-*Z* environments. For the case of RSGs, Jonathan Mackey looked at the effect of surrounding ionising conditions on mass-loss products. In the harsh ionised environment of a young massive cluster, even a neutral wind from a cool supergiant will be ionised, such as for W26 in Westerlund 1. The neutral shell of an AGB star could also be ionised in specific environments, such as a globular cluster.

Evolutionary end products: Planetary nebulae

Moving to the end products of evolution, planetary nebulae, from M < ~ 8 $M_{\odot}$ stars, were the following topic. Joel Kastner gave a contemporary perspective on how wind shaping depends on successive episodes of asymmetry. The fast wind and partially ionised zone is a source of extended X-ray emission and the outer regions of partially ionised, neutral gas, dust and molecules are a rich source for infrared emission. The ChanPlans survey of point and extended X-ray emission in nearby (< 1.5 kpc) PNe was described (Kastner et al., 2012). The X-ray spectra from Chandra can provide the temperature of the hot shocked wind bubble (median ~ 0.7 keV) and its chemistry from the high ionisation emission, e.g., from C and O lines. Some PN exhibit a compact high temperature core (too hot for thermal emission of the PN central star), pointing to the presence of close binaries.

Another aspect of post-AGB evolution was revealed by molecular line mapping, showing the presence of Keplerian discs around the stars, in the presentation by Valentin Bujarrabal. Although the dynamics of AGB and PN expansion seems to be primarily a Hubble law (*viz.* expansion proportional to the distance from the star), some young sources (such as the Red Rectangle and 89 Her) show a compact rotating disc around the star, which may be responsible for launching a jet and decisive to the morphology of the PN. An APEX survey of H_2O maser emission (321 GHz) from water fountain sources was shown by Daniel Tafoya: from multiple epochs, the proper motions of the outflowing maser spots can be traced.

The subsequent evolutionary phase of the central star after the PN, as a white dwarf (WD), was considered by Mark Hollands, who described the detection of metal lines in the atmospheres of cool WDs. In around 15 % of a sample of cool WDs, the lines of Na and Mg are split by the Zeeman effect by fields in the 2–10 MGauss range. The fields may be attributed to a spun-up fossil field or binary merger.

Evolutionary end products: Supernovae

A review of the last steps in the evolution of high-mass stars — as progenitors of supernovae (SNe) — was given by Rubina Kotak. On account of the difficulty of detection and the sparsity of cases, detection of SN progenitors and postgenitors makes confirmation of the progenitor star(s) contentious in the majority of cases. The route to SNIa (Chandrasekhar mass explosion) is generally considered to be either via a WD and a main sequence star (single degenerate route) or two evolved stars such as WDs (double degenerate route), but a variety of other routes is also postulated. The huge increase in monitoring campaigns of SNe and possible SN progenitor sites has led to one system being confirmed as a single degenerate (SN2011fe), but only one possible double degenerate candidate (He2-48, to explode in ~ 700 Myr; Santander-Garcia et al., 2015), has been identified. As sample sizes increase, sub-Chandrasekhar mass SNe are identified, suggesting even that the 1.4 $M_\odot$ explosion may not be the norm. Carolyn Doherty, who received the first prize in the poster competition, showed that super-AGB stars, with masses 6.5–10 $M_\odot$ could be a route for electron capture SNe, leaving behind a neutron star. In the field of core collapse SNe, Kotak showed that there are now some good pre- and post-explosion images showing that high-mass stars can "disappear" after explosion (black hole formation), but the occurrence of core collapse SNe in crowded star-forming regions affects the identification of progenitors and remnants. Imposter SN explosions, perhaps more like the great explosion of η Car, appear to be quite common.

Recent findings on SN 1987A (a core collapse SN of an 18–20 $M_\odot$ RSG) were highlighted by Mikako Matsuura, including the large mass of cold (~ 20 K) dust discovered by ALMA at 450 μm (Matsuura et al., 2014), the detection of emission from cold (~ < 100 K) molecules and the time evolution of the ring and ejecta. The cold dust is possibly amorphous carbon, or carbonaceous, but it is not clear how much of this apparently large amount of dust will survive the reverse shock and be released into the ISM. The cold molecular emission includes some silicate, probably formed deep within the SN explosion. The ring of emission lit up by the shock is now starting to fade and is expected to disappear by ~ 2025. The rise time of type II SNe was treated by Santiago Gonzalez using higher-redshift SNe collected in the Carnegie SN Project to explore the very early times. RSGs with circumstellar material may produce a steeper rise, or a plateau after the peak luminosity.

Noam Soker presented a lively talk on nebulae powered by central explosions emphasising MIJets (Must Include Jets), which are also needed to produce single-star core-collapse SNe. Jets must also be important in forming the circumstellar structures of low-mass stars and the results of hydrodynamic models were presented. Many examples of nebulae were shown with evidence for jets, such as MyCn18, which has similarities to the rings of SN 1987A, and even bipolar nebulae in radio galaxies driven by jets.

Workshop summary

Franz Kerschbaum took up the challenge laid down by Tim de Zeeuw of synthesising the seemingly diverse topics of the workshop. Indeed there were many times during the workshop when it seemed irrelevant whether the observed and modelled structures arose from low- or high-mass stars. Kerschbaum used stills from the Hitchcock film, *The 39 Steps*, as his linking images. Among the topics he noted were, that optical–NIR interferometry is now a mainstream technique, worries that the photocentres of objects, such as Betelgeuse, will change depending on the stellar surface structure (relevant for Gaia), new thoughts about connecting properties and classes and putting objects into new boxes, the role of the larger-scale environment on mass lost by stars and better characterisation of mass loss generally (particularly velocity).

Acknowledgements

The other members of the SOC — Leen Decin, Susanne Hoefner, Roberta Humphreys, Eric Lagadec, Paola Marigo, John Monnier, Anita Richards (with particular appreciation for organisng the poster competition) and Wouter Vlemmings — are warmly thanked for their continuous support. Jason Grunhut and Kate McGuire very efficiently ensured the flow of presentations and speakers. The ESO IT helpdesk provided invaluable support and Sarolta Zahorecz contributed to the local organisation and staffing of the reception desk. Special thanks go to Hildegarde Haems who was responsible for ensuring that so many details of the workshop ran without a glitch, and for whom this was her baptismal workshop at ESO. Stella Chasiotis-Klingner is also gratefully acknowledged for contributing to the logistics and organisation before Hildegarde took over.

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Links

[1] STEPS Workshop programme: http://www.eso.org/sci/meetings/2015/STEPS2015/program.html
[2] Access to poster papers: http://www.eso.org/sci/meetings/2015/STEPS2015/posters.html
[3] Programme of the meeting "The Physics of Evolved Stars": http://poe2015.sciencesconf.org/