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Report on the ESO Workshop

Imaging of Stellar Surfaces

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There have recently been tremendous advances in observational techniques enabling the resolution of the surfaces of stars other than the Sun. Current VLTI instruments, SPHERE on the VLT, and ALMA, as well as other interferometric facilities, have recently succeeded in resolving stellar surfaces. The workshop aimed to bring together observers specialising in different techniques and wavelength regimes, and theoreticians working on stellar atmospheres and stellar structure. We aimed to organise a focused workshop with ample time devoted to the discussion of recent images of stellar surfaces and their extended atmospheres out to a few stellar radii, as well as observational strategies and the relevant underlying physical processes. The workshop was the first to be held in the seminar room of the new ESO Supernova Planetarium & Visitor Centre, and it was also the first workshop for which the new code of conduct for ESO workshops & conferences was in place.

Until very recently, all of our information about the mechanisms affecting the stellar surface came either from indirect observations or from studies of the Sun. The stellar surface is the locus that interfaces the mechanisms taking place in the stellar interior (such as convection and magnetic fields) and diffusion processes which can produce abundance anomalies. Studying stellar surfaces is important for advancing our understanding of these key physical processes.

There have recently been an increasing number of developments in the different observational techniques that enable us to resolve the surfaces of stars other than the Sun. The Very Large Telescope Interferometer (VLTI) is transitioning from its first-generation instruments, which focused on spectro-interferometry, to second-generation instruments, which focus on spectro-imaging and astrometry. The VLTI instruments, the Astronomical Multi-BEam combineR (AMBER) and the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER), have already demonstrated their capability to resolve stellar surfaces, while the second-generation VLTI instruments including the AO-assisted two-object multi-beam combiner GRAVITY and the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE) are coming into operation.

Figure 1. Conference photo.

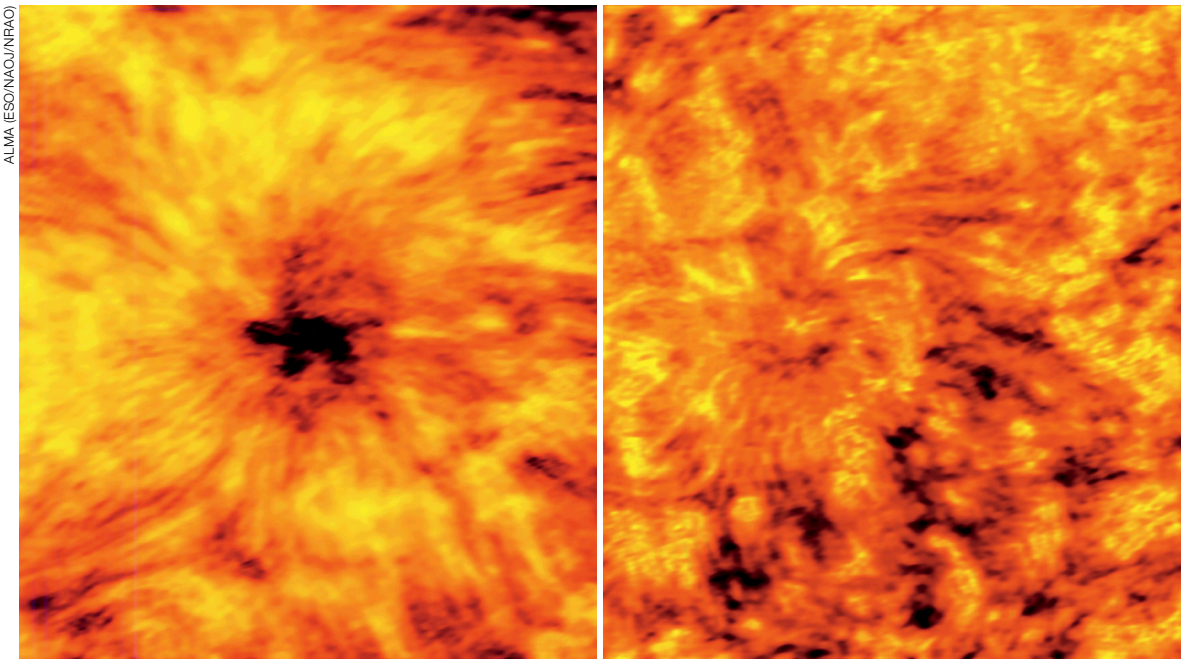
The VLT instrument Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) is also resolving the surfaces of the some of the largest stars. At the same time, ALMA observations using long baselines have succeeded in resolving stellar surfaces at millimetre wavelengths. A number of other interferometers at optical and radio wavelengths have also successfully resolved stellar surfaces, including the Center for High Angular Resolution Astronomy (CHARA), the Karl G. Jansky Very Large Array (VLA), and the Multi-Element Radio Linked Interferometer Network e-MERLIN. Stellar atmosphere models have also been advancing over a similar time frame, from 1D to 3D models that now include the effects of convection. The connection between observations and theoretical stellar atmosphere models is important to constrain models and advance our understanding of physical processes such as pulsation, convection, and chromospheric activity.

The workshop programme was composed of five sessions:
1. The Sun as a star;
2. From the Sun towards evolved stars;
3. Imaging results;
4. Image reconstruction techniques;
5. Prospects.

Claudia Paladini, Wouter Vlemmings, and Alain Chelli led topical discussions on the approaches and challenges to imaging techniques, the coordination of optical and radio programmes, and observational strategies for imaging, respectively. Discussion sessions on individual objects were also held. Andrea Dupree, Lynn Matthews and Christian Hummel led the discussions on Betelgeuse, Mira and Vega respectively. These discussion sessions led to a new collaboration to study Betelgeuse using multiple facilities quasi-simultaneously. We enjoyed the conference venue in the seminar room of the new ESO Supernova Planetarium and Visitor Centre, which we could use for the first time as a test run. We also had a nice time with two shows in the new ESO planetarium that were presented by the ESO Supernova coordinator, Tania Johnston.

The Sun as a star

The “Sun as a star” session opened with an invited talk by Sami Solanki, introducing the main physical processes acting in the solar photosphere and the structures



ALMA (ESO/NAOJ/NRAO)

Figure 2. ALMA images of sunspots in the solar chromosphere at 1.25 and 3 millimetres.

and dynamics that they produce. Sven Wedemayer then outlined what can be learnt from solar observations using ALMA in an invited talk (Figure 2).

The radiation observed by ALMA originates mostly from the chromosphere — a complex and dynamic layer between the photosphere and corona that plays a crucial role in the transport of energy and matter and, ultimately, in the heating of the outer solar atmosphere. The session ended with a presentation by Oskar von der Lühe, in which he described the facilities for the high-angular-resolution imaging of the Sun. Bringing together solar and stellar physicists at this workshop proved to be particularly fruitful. Throughout the meeting, discussions frequently revealed the increasing similarities between these fields.

From the Sun towards evolved stars

The workshop programme continued to illustrate the application of physical concepts from the Sun towards evolved stars, including processes such as chromospheric activity, surface magnetic fields, pulsation and convection. In an invited talk, Andrea Dupree highlighted the ubiquitous signatures of chromospheric activity, variable outflows, and winds in spatially unresolved spectra of giant and supergiant stars. She described how spatially resolved spectra reveal complex structure in these extended stellar atmospheres that we do not understand, and which impacts our understanding of stellar activity, magnetic fields, angular momentum loss, and stellar cluster populations.

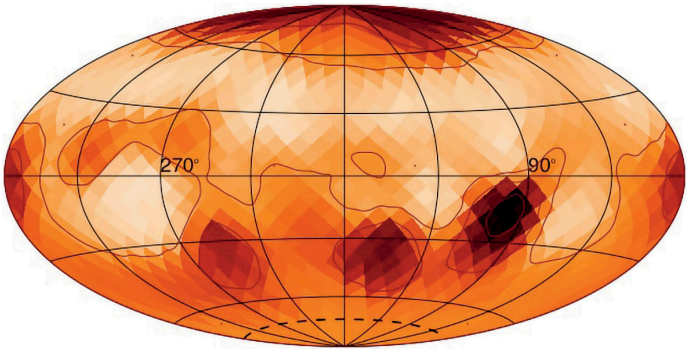
Agnes Lèbre (in an invited talk), and the next speakers described the techniques and recent results from spetropolarimetry, detecting magnetic fields and star spots on the surfaces of Sun-like stars (Emre Isik, Torsten Böhm) a giant and supergiant stars (Agnes Lèbre, Arturo López Ariste). Susanne Höfner (in an invited talk) and Bernd Freytag presented the recent status of 3D simulations of convection for different types of stars, and in particular, the extension of those simulations from solar-type stars to red giant and red supergiant stars.

Basic physical considerations and detailed numerical simulations predict a dramatic increase in the sizes of convection cells during the late phases of stellar evolution. The interplay of large and small convection cells, waves, pulsations, and shocks can give the surface of an AGB star an appearance that is very different from the granulation pattern across the solar surface. Detailed time-resolved imaging is needed to constrain these dynamical processes. Kateryna Kravchenko and Gioia Rau showed comparisons between 3D models and observations using both the tomographic method and near-infrared interferometry with the GRAVITY instrument. Gioia Rau also showed modelling of ultraviolet spectra that contain chromospheric emission lines.

Imaging results

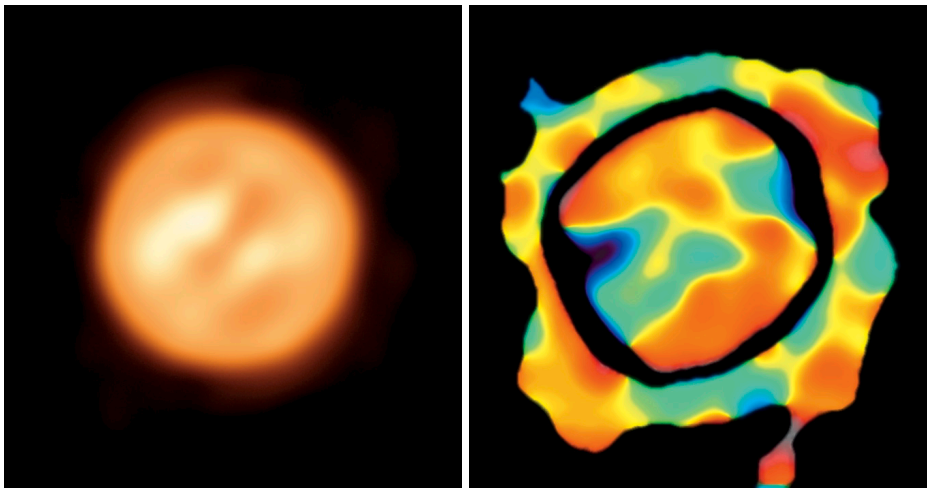
A major theme of the meeting centred on recent imaging results of stellar surfaces obtained at visible/infrared and radio/millimetre wavelengths, and comparing them with models and other complementary observations. Gail Schaefer started this session by providing an invited overview on imaging stellar surfaces with the CHARA array. This included imaging gravity darkening on rapid rotators, star spots on magnetically active stars, convective cells on red supergiants, winds from massive stars, and observations of tidal distortions from Roche lobe filling in interacting binaries.

In an invited talk, Rachael Roettenbacher concentrated on active giants, which have been imaged using photometry, spectroscopy, and, only recently, interferometry (Figure 3). Here, interferometry has provided a way to unambiguously



Roettenbacher et al., 2016

Figure 3. Surface image of the magnetically active star ζ And.



ESO/K. Ohnaka

Figure 4. VLTI reconstructed view (left) and VLTI velocity map (right) of the surface of Antares.

image stellar surfaces without the degeneracies (for example, across hemispheres) experienced by other methods. She discussed recent comparisons of simultaneous interferometric and Doppler images. The CHARA array is the only optical facility presently capable of obtaining the sub-milliarcsecond spatial resolution necessary to resolve surface features of these stars.

Ryan Norris complemented the talks based on CHARA results with an overview of the optimised telescope placements for interferometric imaging. Theo Khouri presented spatially resolved observations of giant stars obtained with the VLT instrument SPHERE in an invited talk. SPHERE is optimally designed to obtain spatially resolved images of the closest and apparently largest giant evolved stars, especially at the shortest visual wavelengths, where its spatial resolution is about 20 milliarcseconds.

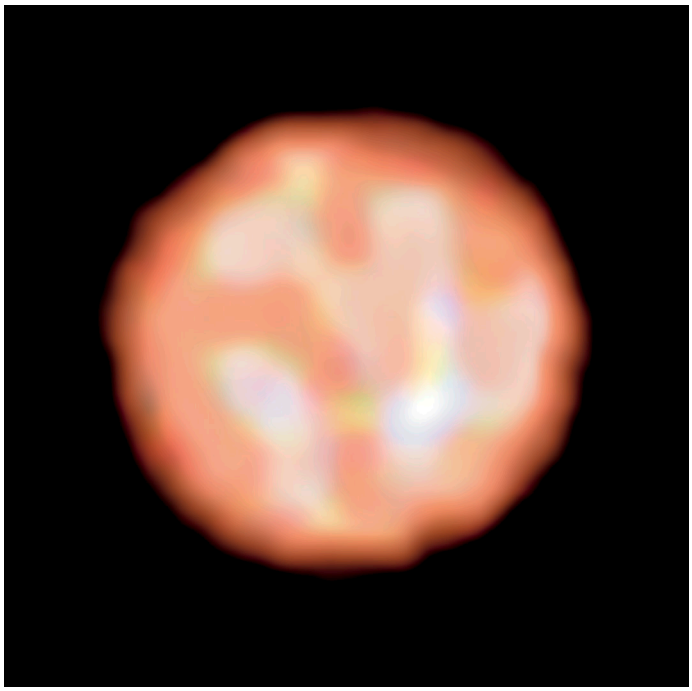
He presented a monitoring campaign of R Doradus that revealed features on the stellar disc varying on timescales of a few weeks, showed results for Mira, and emphasised the benefit of multi-wavelength observation campaigns.

Keiichi Ohnaka, Miguel Montarges, Claudia Paladini, and Markus Wittkowski presented recent aperture synthesis images of various types of evolved star obtained with the instruments AMBER and PIONIER at the VLTI. Keiichi Ohnaka, in an invited talk, presented recent AMBER observations of the red supergiant Antares (Figure 4), which succeeded in not only imaging the surface in the 2.3-micron CO lines in unprecedented detail, but also for the first time showing the complex gas dynamics over the surface and atmosphere of the star in a way that is similar to observations of the Sun. The observations showed upwelling and downdrafting motions of large gas clumps in the atmosphere, suggesting that mass loss in red supergiants may be launched in a turbulent clumpy manner.

Miguel Montarges discussed recent studies of red supergiant stars obtained with the PIONIER instrument in an invited talk, and emphasised the different techniques used to analyse these observations, including intriguing comparisons of interferometric results with spectropolarimetry — as presented earlier in the workshop by Arturo López Ariste and Agnes Lèbre. Claudia Paladini presented stellar surface imaging of the asymptotic giant branch star π^1 Gruis in the PIONIER spectral channels (Figure 5; also see Claudia's article on p. 24). The images of this star are relatively uncontaminated by molecular and dust opacity and show a stellar surface characterised by large convective granulation, constraining the model-expected increase in the sizes of convection cells during late phases of stellar evolution (as also discussed earlier during the workshop by Susanne Höfner and Bernd Freytag).

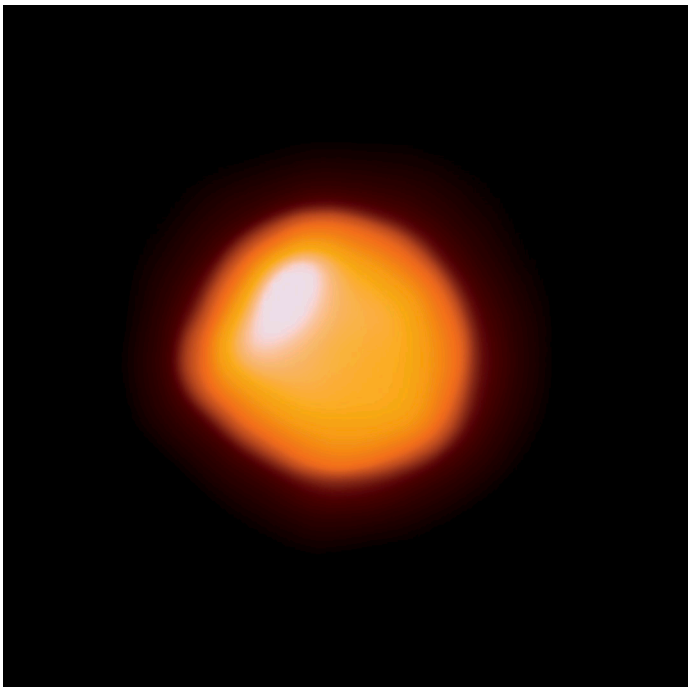
Markus Wittkowski showed PIONIER results for the carbon-rich asymptotic giant branch star R Scl, whose images are dominated by dust seen against the photosphere. This dust is formed in clumps at a few stellar radii, caused by giant convection cells, resulting in large-scale shock fronts, and clumpy molecule and dust formation; this had also been predicted by 3D modelling shown earlier in the workshop by Susanne Höfner. Markus also showed PIONIER images of a few red supergiant stars, which are consistent with the typical contrasts predicted from 3D convection models, but with a distribution of convection cells across the stellar disc that are not randomly distributed but rather appear concentrated in certain areas of the stellar disc.

For imaging results in the radio/millimetre, Eamon O'Gorman gave an invited talk on the history of stellar radio imaging, before showing new results from ALMA (Figure 6) and the JVLA. Wouter Vlemmings went on to present the current status of their ALMA long-baseline observations of four asymptotic giant branch (AGB) stars: W Hya, R Leo, R Dor and Mira. The line and continuum observations at ALMA Bands 4, 6 and 7 trace the temperature and dynamics in their extended atmospheres. The preliminary analysis confirms a previous detection of a hot spot on



ESO/C. Paladini

Figure 5. The surface of the red giant star π^1 Gruis from PIONIER on the VLTI.



ALMA (ESO/NAOJ/NRAO)/E. O'Gorman/P. Kervella

Figure 6. Betelgeuse, as captured by ALMA.

W Hya, and reveals unexpected lines in most of the sources, as well as possible fast rotation in the atmosphere of one of the stars. Lynn Matthews described their JVLA and ALMA studies, which reveal the evolving shapes of the radio photospheres of AGB stars. The data provide evidence that the shapes of the radio photospheres of AGB stars change on timescales of several months or more. Additionally, the data reveal signatures of brightness asymmetries and non-uniformities. The results are consistent with manifestations of large-scale irregular convective flows on the stellar surfaces.

The application of new imaging techniques to the interpretation of these data was also discussed. Ka Tat Wong outlined a recent study of the non-equilibrium chemistry of oxygen-rich AGB stars, performed using ALMA. Chemical models suggest that pulsation-driven shocks propagating from the stellar surfaces of oxygen-rich evolved stars to the dust formation zone trigger non-equilibrium chemistry in the shocked gas near the star, including the formation of carbon-bearing molecules in the stellar winds dominated by oxygen-rich chemistry. The talk focused on observations of IK Tau and Mira performed in late 2017, with a particular emphasis on HCN.

Finally, Liz Humphreys described how ALMA long-baseline observations had revealed an unusual morphology for the SiO maser emission towards the binary system Mira AB. The effect of binary companions on the near-circumstellar environment of AGB stars is, in general, an open question. The ALMA data probed this region of Mira A using SiO emission. Most importantly, the data locate SiO masers with respect to the star, unlike with lower-frequency observations. They also indicate an impact of the binary companion on gas within about 10 stellar radii of Mira A. These types of studies, using high-frequency SiO masers, can provide a new avenue for understanding the influence of binaries on AGB mass loss and shaping their envelopes.

Image reconstruction techniques

John Young was invited to provide an overview of the various available algorithms for synthesis imaging at visible and infrared wavelengths. He described reconstruction biases that can follow from non-optimal choices of regularisation functions and their strengths, and their potential impact on the physical interpretation of the results. His talk was illustrated with examples of stellar surface imaging from real datasets.

For the radio to millimetre regime, Bill Cotton gave an invited talk on radio imaging of the envelopes of evolved stars, paying particular attention to the technical differences between radio and optical/infrared interferometry. He described how milliarcsecond resolution of very bright, i.e., non-thermal, emission from molecular masers in the envelopes of evolved stars can be achieved using VLBI techniques with baselines of thousands of kilometres.

Prospects

Gioia Rau started the session on future prospects with an invited talk about imaging the surfaces of stars from space. She reviewed results obtained so far from space with the benefit of extending the wavelength coverage, including ultraviolet spectra taken with the International Ultraviolet Explorer (IUE), as well as ultraviolet images obtained with the Hubble Space Telescope (HST) of Mira and Betelgeuse. She then investigated the prospects for

infrared imaging with the James Webb Space Telescope (JWST), and finished with a forward look towards space-based large-baseline Fizeau interferometers such as the ultraviolet-optical Stellar Imager (SI) Vision Mission.

In an invited talk, Dainis Dravins explained the technique of intensity interferometry as pioneered by Robert Hanbury Brown and Richard Twiss (Hanbury Brown & Twiss, 1956). He suggested a possible application of this technique using the Cherenkov Telescope Array (CTA), enabling spatial resolutions of tens of microarcseconds, as well as a possible application using the mirror segments of ESO's Extremely Large Telescope (ELT). Anita Richards gave an invited talk on using the full capabilities of ALMA, e-MERLIN, the Next-Generation VLA (NG-VLA) or the Square Kilometre Array (SKA) with long baselines to investigate the transport of mass and energy through the layers above the photosphere, and to test whether the clumpiness of the wind could be related to local ejection of mass from the stellar surface.

Antoine Merand concluded the workshop with an invited talk on the VLTI facility as an imaging machine, outlining how the VLTI could evolve to include and operate additional telescopes, as well as the improvements and limitations related to imaging stellar surfaces. Earlier in the workshop, Xavier Haubois had shown how some improvements were already being implemented, with a description of the newly introduced imaging operations scheme at the VLTI to allow optimised and adaptive uv plane coverages.

Julien Woillez presented the idea of deploying an agile 12-telescope single-mode visible interferometer on the Paranal mountain that would be optimised to image bright stars. Earlier in the workshop, Anders Jorgensen and Gerard van Belle had considered the Navy Precision Optical Interferometer (NPOI), proposing its use for the imaging of stellar surfaces with the new Classic beam combiners, the Visible Imaging System for Interferometric Observations (VISION) beam combiners, as well as with its upgrade, the Precision Array of Large-Aperture New Telescopes for Image Reconstruction (PALANTIR).

Main conclusions and the way ahead

A number of recurring themes were identified over the course of the workshop. It was noted that an increasing synergy arises from interdisciplinary approaches using fundamentally similar techniques developed for solar observations, spectropolarimetric observations of stars, and spectro-interferometric imaging of stars. Comparisons of detailed surface features derived at similar epochs from spectropolarimetry, Doppler imaging, and interferometric imaging, both for magnetically active stars and red supergiants, were intriguing and worth continuing. Comparing interferometric images with 3D modelling was also valuable. These approaches require time-domain imaging and ideally involve observing the same sources with multiple facilities over the same time period.

Another recurring theme was the hypothesis that clumpy mass loss, at least for red supergiants, is related to localised ejection from the stellar surface. Again, in order to test this hypothesis, coordinated multi-wavelength, multi-facility observations are required to follow the transport of energy and mass from the stellar surface to the outermost layers of the atmosphere and the wind. While it was generally accepted that stars, including cool evolved stars, show chromospheric emission, no conclusion was reached about the impact of this emission on the mass-loss processes in evolved stars.

In technical terms, there was an interesting suggestion that optical interferometric imaging could benefit from combining different baseline lengths for the same source using different interferometric facilities operating at comparable wavelengths. The workshop concluded with a discussion of the impact of stellar surface imaging on the field of stellar physics in general, as well as on the further development of interferometric facilities.

Demographics

The Science Organising Committee (SOC) consisted of seven members (3 female, 4 male) from ESO, Germany, Sweden, and the USA. The SOC suggested and voted on invited speakers to present highlights and overviews in the different sessions. The result was a fairly balanced representation of invited speakers in terms of gender, career stage and geographical distribution. Invited speakers (40% female, 60% male) came from Belgium (1), Chile (1), ESO (1), France (1), Germany (1), Ireland (1), Sweden (4), UK (2), and USA (3). Participants who submitted contributed talks and poster presentations were accommodated as requested. In total, the workshop had 60 participants (25% female, 75% male) from USA (13), ESO (11), France (8), Sweden (8), Germany (5), Belgium (3), Turkey (2), UK (2), Poland (1), Austria (1), Spain (1), Australia (1), Ireland (1), Chile (1), and Singapore (1). Among the participants, 10% were PhD students (4 female, 2 male). We did not ask participants beyond PhD students for their career stage, but believe that they were evenly distributed across the early-, mid-, and late-career stages.

Acknowledgements

The other members of the scientific and local organising committees — Stella Chasiotis-Klingner, Bernd Freytag, Xavier Haubois, Tania Johnston, Kateryna Kravchenko, Lisa Löbling, Lynn Matthews, Claudia Paladini, Oskar von der Lühe, and Ke Wang — are warmly thanked for their continuous support. We are grateful to everybody else who was involved in the preparations for this workshop, and in particular to those who helped make this workshop happen in the ESO Supernova Planetarium & Visitor Centre before its official opening, including Sandor Horvath, Tania Johnston, Fabian Reckmann, Jürgen Riesel, Erich Siml, Ana Vukovic, and the teams from the ESO education and Public Outreach Department, Facility Logistics Transport and catering at ESO.

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Roettenbacher, R. et al. 2016, Nature, 533, 217

Links

[1] Workshop programme: https://www.eso.org/sci/meetings/2018/Imaging-Stellar-Surfaces/program.html