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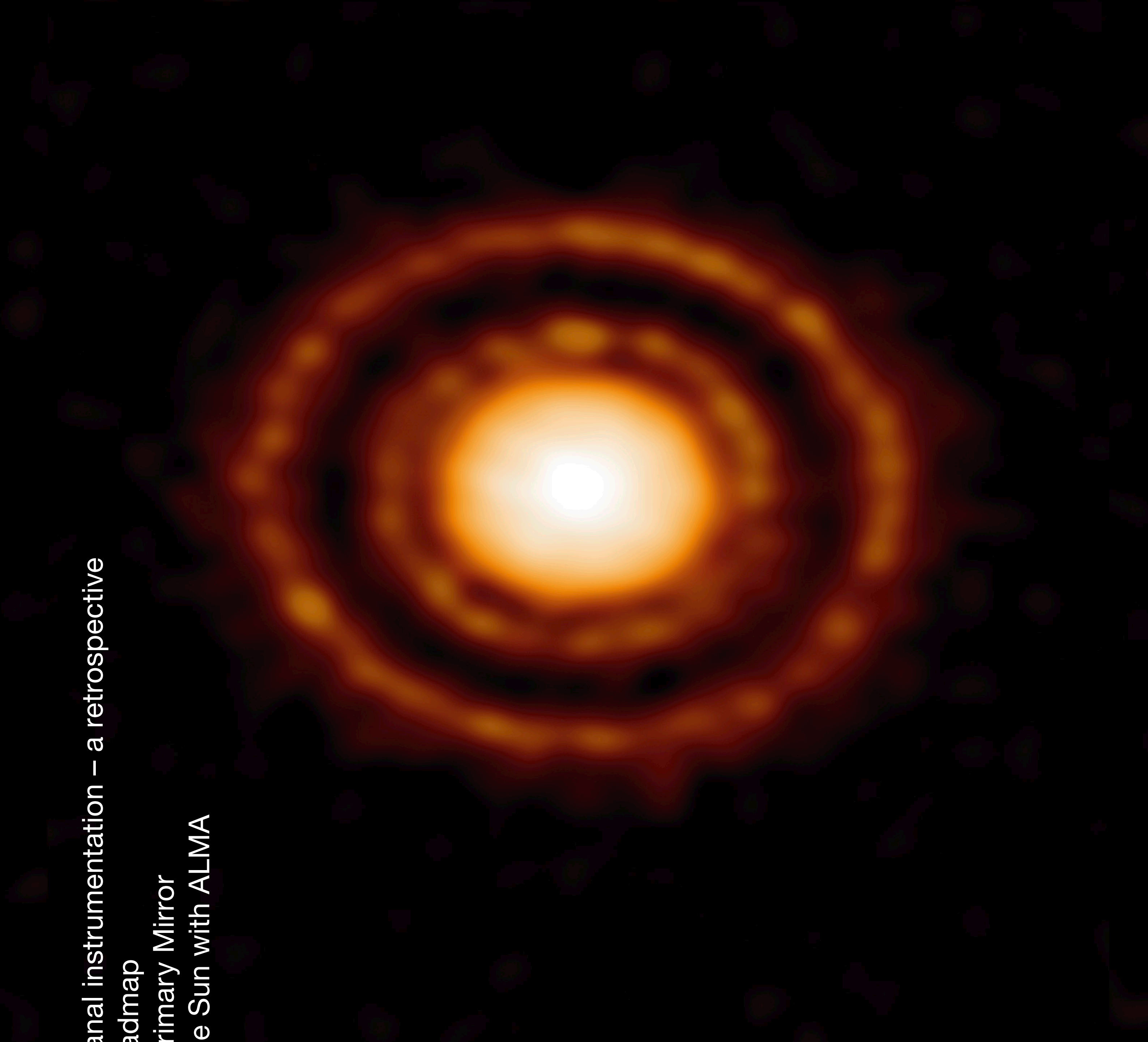

La Silla Paranal instrumentation – a retrospective
The VLTI roadmap
The ELT's Primary Mirror
Exploring the Sun with ALMA

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40+ Years of Instrumentation for the La Silla Paranal Observatory

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As ESO Period 100 comes to a close, I look back at the development of ESO's instrumentation programme over more than 40 years. Instrumentation and detector activities were initially started by a small group of designers, engineers, technicians and astronomers while ESO was still at CERN in Geneva in the late 1970s. They have since led to the development of a successful suite of optical and infrared instruments for the La Silla Paranal Observatory, as testified by the continuous growth in the number of proposals for observing time and in the publications based on data from ESO telescopes. The instrumentation programme evolved significantly with the VLT and most instruments were developed by national institutes in close cooperation with ESO. This policy was a cornerstone of the VLT programme from the beginning and a key to its success.

Instrumentation: the interface between ESO and its users

Most astronomers in Europe are familiar with ESO as it is today, with its three observing sites in Chile, the Extremely Large Telescope under construction, the scientific and administrative centre in Santiago, headquarters in Garching, and as the European partner in the Atacama Large Millimeter/submillimeter Array (ALMA). However, they may not be aware of the modest goals (as compared to today's achievements) set by ESO's founders in the ESO Convention of 1962, which was signed by representatives from Belgium, France, the Federal Republic of Germany, the Netherlands and Sweden. An excerpt from the English version of the document states[1], "The purpose of the Organisation shall be to build, fit out and operate an astronomical observatory situated in the southern hemisphere. The initial programme of the Organisation shall comprise the construction, installation and operation of an observatory in the southern hemisphere, consisting of:

a. a telescope with an aperture of about 3 metres;
b. a Schmidt telescope with an aperture of about 1.20 metres;
c. not more than three telescopes with a maximum aperture of 1 metre;
d. a meridian circle;
e. the auxiliary equipment needed to carry out research programmes with the instruments listed in a., b., c. and d. above…".

When reading this text for the first time, I was amused to see that only the telescopes and the meridian circle only granted the title of "research instruments" while everything else was more modestly described as "auxiliary equipment". The first telescopes erected at the La Silla site (with diameters of 50 cm, 1 m and 1.52 m) were equipped with "auxiliary equipment" supplied by institutes in the member countries: photometers for the smaller telescopes and high-resolution spectrographs for the 1.52-metre telescope. These instruments mostly duplicated similar ones in operation at European sites and were conceived to carry out stellar work in the southern hemisphere, reflecting the focus of European astronomy at that time.

This was in the early 1970s, when the North American observatories were increasingly starting to focus their scientific research on extragalactic targets, spurred on by the discovery of the first quasars, which changed our view of the Universe. European astronomy needed larger telescopes and modern instrumentation to compete with these exciting scientific developments. ESO's founders had a vision that this was best achieved by joining forces, but progress was initially slow.

The 3.6-metre telescope, ESO's main project, saw first light in 1976. Lodewijk Woltjer, ESO Director General from 1975 to 1987, writes in his book (Woltjer, 2006), "When I came to ESO in 1975, it was evident that there was no real plan to effectively use the 3.6 m telescope for contemporary science. There also would be no suitable instrumentation to attach to the telescope." An instrumentation development programme was started while ESO was still at CERN in Geneva (between 1972 and 1980). This was further expanded when the Organisation moved to its new Headquarters in Garching, Germany. Two instrumentation groups, one optical and one infrared, were set up. They were led by astronomers who reported directly to the Director General. A dedicated group of engineers was put to work on the procurement and testing of optical and infrared detectors and their control systems within the Technical Division. A committee of astronomers from the member countries and from ESO, later called the Scientific Technical Committee, provided the guidelines and general specifications for these new developments. During those early years, when ESO began to build its reputation, the overall structure was agile and flexible and ensured that strategic choices in the development of instruments were driven by the science.

The importance of instrumentation and the associated detectors to observational astronomy cannot be underestimated. Instruments serve as a key interface between an observatory and its scientific users. Along with good atmospheric conditions and telescopes that operate smoothly, instrumentation can determine the scientific success of an observing run. If the instruments operate well and can compete with those available elsewhere, astronomers will obtain high-quality data that ultimately gives them a more effective long-term impact in their field of research. This, in short, is the primary goal of an observatory.

1978–1998: two decades of "fast and furious" growth

The instrumentation and detector programme started to show results at the telescopes in Chile at the end of the 1970s. First, the Coudé Échelle Spectrograph (CES) with a 1D digital detector become operational in the coudé room of the 3.6-metre telescope, fed by the newly erected 1.4-metre Coudé Auxiliary Telescope (CAT) and, a few years later, by an optical fibre from the 3.6-metre. An off-the-shelf instrument, the Boller and Chivens grating spectrograph, was acquired to offer the possibility to observe faint objects at the 3.6-metre. It initially used a 1D Image Dissector Scanner (IDS) detector.

Two instruments designed and built by ESO then become operational in 1984

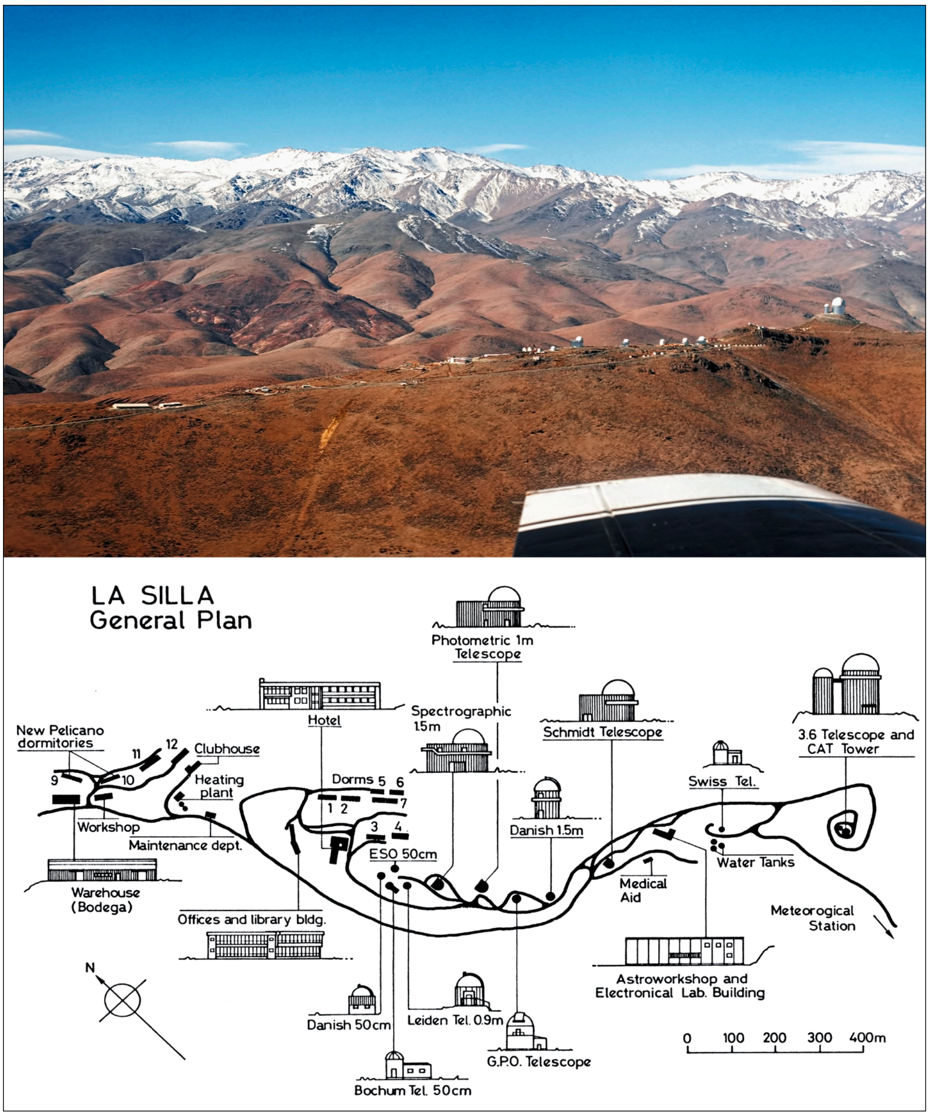

Figure 1. Below is the hand-drawn map of the La Silla Observatory from the beginning of the 1980s, before the installation of the 2.2-metre telescope and the NTT. A photo from the same epoch was taken from the plane that was used to commute staff from Santiago to the Pelicano airstrip close to La Silla. The small plane was in use until the early 1990s.

and 1985: CASPEC, an efficient cross-dispersed échelle spectrograph and the ESO Faint Object Spectrograph & Camera (EFOSC). Both used silicon charge-coupled device (CCD) detectors — the first to operate at the 3.6-metre telescope. The high efficiency of the optics, coupled with the high quantum sensitivity of the CCDs, boosted the performance of these instruments and, for the first time, gave European astronomers the possibility of competing on crucial observing modes with their colleagues at other 4-metre-class telescopes worldwide. In the mid-1980s these two instruments regularly used around 60 % of the telescope nights.

EFOSC deserves a special mention. This innovative transmission optics instrument was the first major work by the ESO designer Bernard Delabre, who recently retired. It was followed by an upgraded version, EFOSC2, which served as the prototype for the very successful FORS instruments at the Very Large Telescope (VLT). As noted by de Zeeuw et al. (2017), EFOSC clones or derivatives have been built for telescopes distributed across almost all continents. Delabre put forward many other original ideas over his 40 years at ESO, with the consistent aim of designing more efficient instruments using affordable optics. Most VLT instruments are based on his designs or incorporate his ideas. I worked with him on the definition of several instruments (EMMI, FORS, UVES, X-shooter), which was always a gratifying experience. On receiving a set of requirements, such as wavelength range, spectroscopic resolution, image scale and the likely properties of the detector, he would create a preliminary, often original, design in just a few days. A robust discussion with the project team would follow, about performance, feasibility and cost, and would eventually lead to a final configuration that formed part of an instrument proposal.

Table 1 lists the most-demanded instruments at the three most powerful La Silla telescopes, along with their period of operation and the number of publications that have used their data. The years from 1978 to 1998 saw a spectacular growth in ESO facilities, with the arrival of new instruments at the 3.6-metre telescope, the installation of the 2.2-metre Max-Planck-Gesellschaft (MPG)/ESO telescope and the completion of the New Technology Telescope (NTT) with three fixed instruments at its two Nasmyth foci. All of this was during the construction of the VLT. The growing interest and confidence of the community in the use of ESO's facilities was reflected in the number of observing proposals, which went from about 150 in 1978 to over 550 in 1995 (Patat et al., 2017).

The use of near-infrared (NIR) instruments was initially limited by the lack of suitable detectors. In the first part of this period, the first NIR spectrograph, IRSPEC, started operating at the 3.6-metre telescope with just a 32-diode linear detector, which was upgraded to a 58 × 62 pixel InSb array when the instrument was moved to the NTT in 1991. A few years later when the 1k × 1k pixel HgCdTe infrared arrays become available, ESO quickly put them into operation using two new instruments, SOFI at the NTT and ISAAC at the VLT. The two were immediately in high demand and delivered a rich harvest of scientific results.

Instrument name	Acronym	Telescope	Instrument type	Operating time	No. papers
Bollers & Chivens	B & C	3.6 m	Grating spectrograph	1978–1990	N/A
Cassegrain Échelle Spectrograph	CASPEC	3.6 m	Échelle spectrograph + spectropolarimetric mode	1984–1999	N/A
ESO Faint Object Spectrograph and Camera 1–2[a]	EFOSC1–2	3.6 m, NTT	Spectrograph, imager, polarimeter	1985 →	690
Infrared Spectrometer	IRSPEC	3.6 m, NTT	NIR 1D spectrograph	1987–1996	N/A
Thermal Infrared Multi-Mode Instrument[b]	TIMMI2	3.6 m	MIR spectrograph & imager	2000–2006	97
High Accuracy Radial velocity Planet Searcher[b]	HARPS	3.6 m	Échelle spectrograph	2003 →	689
ESO Multi-Mode Instrument	EMMI	NTT	Spectrograph & imager	1990–2008	689
Son of ISAAC	SOFI	NTT	NIR spectrograph & imager	1998 →	809
SUperb Seeing Instrument 2	SUSI2	NTT	Imager	1998–2008	130
Wide Field Imager[b]	WFI	2.2 m[d]	Wide field imager	1998–2013	515
Fibre-fed Extended Range Optical Spectrograph[b,c]	FEROS	2.2 m[d]	Échelle spectrograph	2003–2013	676

Table 1. The most popular instruments at the largest La Silla telescopes. The publication statistics are from 1 January 2000 to 31 January 2018, and are therefore unavailable for some of the earliest instruments. Some of the instruments were built by consortia; please see the Notes at the end of the article for further information on the Principal Investigators and teams.

While the ESO-built instruments took up the bulk of the observing time at the 3.6-metre telescope and at the NTT, the telescopes were also used by visitor instruments or part-time instruments supplied by national institutes. Most notably, the three adaptive optics (AO) systems (Come-On, Come-On$^+$ and the ADaptive Optics Near Infrared System [ADONIS]) and a mid-infrared (MIR) version of EFOSC called TIMMI (superseded by TIMMI2), were developed in France and played a key role as scientific tools and as test benches for future VLT instruments.

Starting in 1993 at the NTT, a high-resolution NIR camera, SHARP (built in Germany), was used by a dedicated team for observations of the Galactic Centre, opening up a very successful line of research that has continued on to the present day with the VLT instruments SINFONI and GRAVITY, the latter only commissioned in 2017. A later addition to the list of instruments supplied by national institutes was the high-stability échelle spectrograph HARPS in 2003, which is installed in the coudé room of the 3.6-metre telescope and is now the only instrument offered at that telescope. As shown in Table 1, data taken with the instrument have been used for close to 700 publications since its installation, making it the most successful planet hunter in ground-based astronomy.

What I have outlined in this article is a somewhat selective version of two decades of the history of instrumentation at the La Silla Observatory. Other telescopes, the ESO 1-metre Schmidt, which was dedicated to the southern sky photographic survey, the spectroscopic ESO 1.52-metre and the Danish 1.54-metre with its CCD camera (the first to be installed on La Silla) and later host to the Danish version of EFOSC, also contributed significantly to the scientific growth of the user community. Additional instruments served a large number of users well; for example, the prime focus cameras and OCTOPUS (a multi fibre spectrograph at the 3.6-metre telescope), the two Boller & Chivens spectrographs at the 1.52-metre and the 2.2-metre telescopes, FEROS at the 1.52-metre telescope, and infrared cameras IRAC and IRAC2 at the 2.2-metre telescope. These were particularly useful in building the expertise that later bore fruit at the VLT. More details on various projects conducted over 50 years of ESO can be found in Madsen (2012).

The VLT era (1999–2018): collaborating with ESO Member State institutes

Construction of the VLT was approved by the ESO Council in December 1987. This was well before NTT first light in March 1989, so the exceptional image quality obtained in the first NTT observations, thanks to the newly implemented active optics, was as yet unknown. A number of other factors led to the approval of the VLT, including: the preparatory work that ESO carried out with technical studies in house; the organisation of meetings focussing on the science and design challenges of large telescopes; the favourable economic situation in ESO Member States; and the growing interest within the scientific community and amongst the public about new astronomical discoveries from the ground and from space. The good results obtained with the first ESO-built instruments, like CES, CASPEC and EFOSC, also helped to build confidence in ESO in the scientific community and in members of the ESO Council.

Discussions about VLT instrumentation started very early in the project, with VLT Working Groups, focused on different observing modes and composed of external and ESO scientists, set up in 1985. After these interactions, the first version of the VLT instrumentation plan was released in 1990 (D'Odorico et al., 1991), more than 8 years before first light. It already contained an outline of the first instruments to be built and the strategy for their procurement.

The cornerstones of the proposed approach, which was new for ground-based observatories, were:
– The majority of instruments had to be built by institutes, with ESO contributing standard items and selected subsystems.
– Instruments had to comply with a set of verifiable specifications and would be subject to regular review during construction.
– Hardware costs were to be paid by ESO, while the staffing provided by the institutes would be compensated by observing nights with the instrument (called Guaranteed Time Observations [GTO]).

Instrument name	Acronym	Type	Operation time	Team information
FOcal Reducer/low dispersion Spectrograph 1	FORS1	Vis. I,S,P	1999–2009	PI I. Appenzeller, Co-PIs R. Kudritzki & K. Fricke (Germany)
Infrared Spectrometer And Array Camera	ISAAC	NIR I,S	1999–2013	PI A. Moorwood (ESO), PM A. van Dijsseldonk, IS J. G. Cuby
FOcal Reducer/low dispersion Spectrograph 2	FORS2	Vis. I,S, P	2000 →	See FORS1
UltraViolet-Visual Échelle Spectrograph	UVES	Vis. Éch.	2000 →	PI S. D'Odorico (ESO), PM H. Dekker, IS A. Kaufer
Nasmyth Adaptive Optics System (NAOS)-CONICA	NACO	NIR AO I,S	2002 →	PIs R. Lenzen (Germany) & G. Rousset (France)
VIsible Multi-Object Spectrograph	VIMOS	Vis. MOS	2003 →	PI O. LeFèvre (France), Co-PI P. Vettolani (Italy)
Fibre Large Array Multi Element Spectrograph	FLAMES	Vis. MFS	2003 →	PI L. Pasquini (ESO), Co-PIs A. Blecha (Switzerland), C. Cacciari (Italy), M. Colless (Australia), F. Hammer (France)
Spectrograph for INtegral Field Observations in the Near Infrared	SINFONI	AO NIR IFS	2004 →	PIs N. Thatte & F. Eisenhauer (Germany), Co-PI T. de Zeeuw (Netherlands), H. Bonnet
VLT Imager and Spectrometer for mid-InfraRed	VISIR	MIR I-S	2005 →	PI P. O. Lagage (France), Co-PI W. Pel (Netherlands)
Cryogenic InfraRed Échelle Spectrometer	CRIRES	NIR Éch.	2007–2014[e] →	PI H.-U. Käufl (ESO), PM J. Pirard
High Acuity Wide field *K*-band Imager	HAWK-I	NIR I AO	2008 →	PI M. Casali (ESO), PM J. Pirard, IS M. Kissler-Patig
X-shooter	X-shooter	NIR Éch.	2009 →	PIs S. D'Odorico (ESO), F. Hammer (France), L. Kaper (Netherlands), P. Kiærgaard (Denmark), R. Pallavicini (Italy), PM H. Dekker, IS J. Vernet
K-band Multi-Object Spectrograph	KMOS	NIR MOS	2013 →	PIs R. Sharples (UK), R. Bender (Germany)
Multi Unit Spectroscopic Explorer	MUSE	Vis. IFS AO	2014 →	PI R. Bacon (France), Co-PIs T. de Zeeuw (Netherlands), S. Lilly (Switzerland), H. Nicklas (Germany), J. P. Picat (France), M. Roth (Germany)
Spectro-Polarimetric High-contrast Exoplanet REsearch instrument	SPHERE	NIR AO I,S,P	2015 →	PI J. L. Beuzit (France), Co-PI M. Feldt (Germany)
Échelle SPectrograph for Rocky Exoplanet- and Stable	ESPRESSO	Vis. Éch.	2018 →	PI F. Pepe (Switzerland), Co-PIs S. Cristiani (Italy), R. Rebolo-Costa (Spain), N. Santos (Portugal)
Enhanced Resolution Imager and Spectrograph	ERIS	NIR I,S AO	2020 (tbc)	PI R. Davies (Germany), Co-PIs S. Esposito (Italy), M. Kenworthy (Netherlands), M. Macintosh (UK), S. Quantz (Switzerland)
Multi Object Optical and Near-infrared Spectrograph	MOONS	Vis.–NIR MFS	2021 (tbc)	PIs J. Afonso (Portugal), M. Carollo (Switzerland), M. Cirasuolo (ESO), R. Maiolino (UK), H. Flores (France), T. Oliva (Italy), L. Vanzi (Chile),

Table 2. VLT Instruments from first light in 1999 to 2018. The second column lists the wavelength bands (Vis. visible, NIR near-infrared, MIR mid-infrared) and instrument capabilities, which are described as follows: AO adaptive optics, Éch échelle spectroscopy, I imager, IFS integral field spectroscopy, MFS multiple fibre spectroscopy, MOS multi-object spectroscopy, P polarimetry and S spectroscopy. The Team information lists the Principal Investigators (PIs) and Co-PIs. The latter were members of the consortium responsible for the project in their institute or for their country. In the case of ESO-led projects, project managers (PM) and instrument scientists (IS) are also given.

The resulting instrument collaborations included advantages for both parties. For ESO it enabled an ambitious instrumentation programme within budget and on schedule; it gave access to unique expertise that was nurtured in national institutes; and it fostered a sense of ownership of the VLT programme in a significant fraction of the astronomy community. For the institutes it led to the creation of competent, multidisciplinary instrument teams around an ambitious project, and made it easier to obtain funding from national agencies to develop the necessary infrastructure, including integration and testing facilities.

Finally, GTO provided the opportunity to carry out programmes that could have a significant scientific impact. This synergy between ESO and the different national groups has produced a unique set of high-quality instruments and greatly contributed to the growth of ground-based astronomy in Europe. Seven out of 11 first-generation instruments were built outside ESO and this percentage is even higher for the second generation. The contribution of ESO to the external instruments has been significant; all the detector systems (visible and NIR) were procured, integrated and optimised by ESO. Other significant examples of ESO deliverables are the AO systems for SINFONI, MUSE and HAWK-I and the large échelle grating unit for ESPRESSO.

Table 2 lists all of the instruments at the VLT today as well as the two that have been decommissioned and two that are in an advanced stage of construction. The operational lifetime of the first instruments has clearly exceeded the original estimates of a maximum of ten years of operation. This has been made possible by the homogeneous and high standards that were set for all instrument specifications and by effective maintenance procedures at the Observatory. Technical interventions and upgrades have been carried out when needed to keep instrument performance competitive. A detailed analysis of statistics of ESO observing proposals, and of the number of publications and the corresponding citations, has been carried out by Leibundgut et al. (2017) and concludes, "all VLT instruments are in constant demand, display a good scientific return and show significant scientific impact". The fact that citation counts continue to increase for all operational instruments is an indication of their ongoing competitiveness.

Interferometry was a key objective of the VLT from its conception. Table 3 lists the

Instrument name	Acronym	Instrument type	Operation time	Team information
VLTI Commissioning Instrument	VINCI	*K*, 2-beam	2001–2011	PI V. Coudé du Foresto (France), Co-PI P. Kervella (France, ESO)
Astronomical Multi-BEam combineR	AMBER	*H-K*, 3-beam, SC	2004 →	PI R. Petrov (France), Co-PIs F. Malbet (France), K.-H. Hofmann (Germany)
Mid-infrared Interferometric instrument	MIDI	*N*, 2-beam, SC	2003–2015	PI C. Leinert (Germany), Co-PIs G. Perrin (France), R. Waters (Netherlands)
Precision Integrated-Optics Near-infrared Imaging ExpeRiment	PIONIER	*H-K*, 4-beam, I	2011 →	PIs J. P. Berger, J. B. Le Bouquin (France)
GRAVITY	Gravity	*K*, 4-beam, I Astr., SC	2016 →	PI F. Eisenhauer (Germany), Co-PIs K. Perraut (France), G. Perrin (France), C. Straubmeier (Germany), W. Brandner (Germany), A. Amorim (P)
Multi-AperTure mid-Infrared SpectroScopic Experiment	MATISSE	*L-N*, 4-beam, I, SC	2019 →	PI B. Lopez (France), Co-PIs T. Henning (Germany), G. Weigelt (Germany), W. Jaffe (Netherlands), F. Vakili (France)

Table 3. VLTI instruments and key information about the instruments and the instrument building teams. PIs and Co-PIs are defined as in Table 2. The instrument type lists the wavelength band covered, the number of coherently combined telescope beams and the type of instrument using the following abbreviations: Astr. astrometry; I 2D imaging; and SC spectroscopic capability.

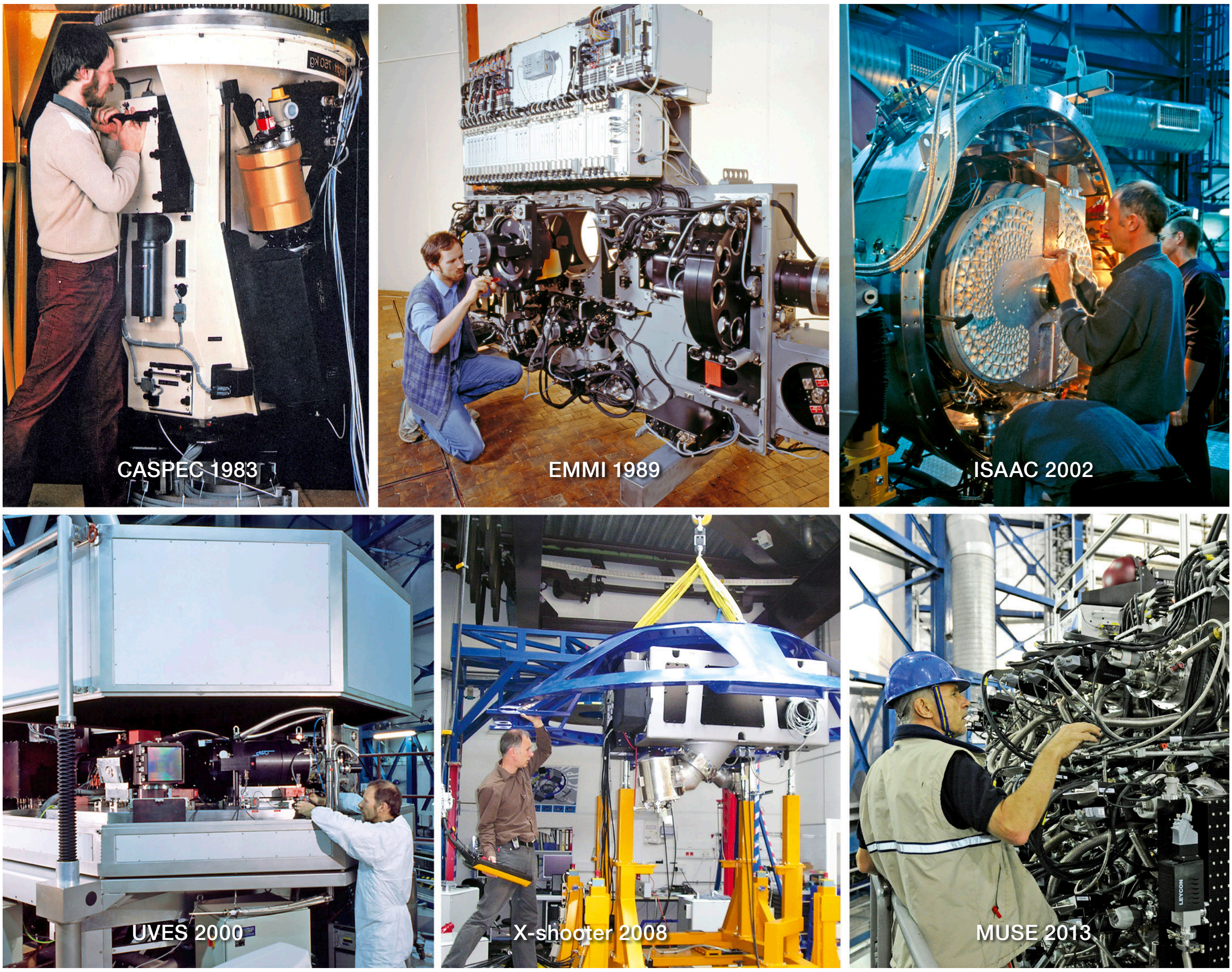

Figure 2. This mosaic of ESO instruments spanning 30 years of ESO history illustrates that the organisation is made up of individuals, not just of a sequence of projects. In this case the photos show Jean-Louis Lizon á l'Allemand, the long-time head of the Integration and Cryogenic Group, at work during the testing and integration of instruments for La Silla and Paranal. Equivalent pictures could be made up for many other members of the ESO personnel in Garching and in Chile. It is a useful reminder of the importance of in-house technical expertise and of the dedication of ESO staff to their unique jobs.

main VLTI instruments. These are located at the focus for coherent combination of the light beams from the four dedicated 1.8-metre Auxiliary Telescopes (ATs) or from the 8-metre telescopes. In practice, owing to the special requirements and exploratory nature of the interferometric observations, all of these instruments have been developed by national institutes in close collaboration with the VLTI group at ESO. Coherent combination of the light from the 8-metre Unit Telescopes has been carried out for more than a decade now, but ESPRESSO, a high stability échelle spectrograph that is being commissioned at the Paranal Observatory, is the first instrument which can be fed by the incoherent beam/(s) from either a single telescope or multiple telescopes. It will open up new parameter space in both limiting magnitude and wavelength accuracy, in high resolution spectroscopy at ESO.

In the last decade the cooperation between ESO and its community on Paranal has not been confined to the VLT but has led to the installation of two additional powerful telescopes. The VISTA 4-metre survey telescope with an infrared camera (VIRCAM), covering a field of 1.65 degrees in diameter, was delivered by the UK in 2007 as an in-kind payment when it joined ESO. The 2.5-metre VLT Survey Telescope (VST) was installed by the Italian National Institute for Astrophysics in 2011 and is equipped with a 1 × 1 degree field CCD camera (OmegaCAM), which was developed by a consortium from the Netherlands, Germany, Italy and ESO.

We are now approaching 20 years of VLT operation. The procedure set up more than 25 years ago for the definition and procurement of instruments has been consolidated and proven to be very successful. It has inspired similar approaches at all other major observatories worldwide. The 39-metre ELT telescope project that ESO is embarking on now opens up a new scenario. The unique properties of the AO-based telescope — the largest photon collecting area ever in one telescope — and the need to optimise the use of precious observing time require new thinking in the selection and design of instrumentation as well as in its operating mode(s). These are the exciting challenges that the ESO community faces over the next decade.

Acknowledgements

The instrumentation effort at ESO has involved the contributions of more than a hundred members of ESO staff over the last 40 years. This includes designers, managers, engineers, technicians, physicists and astronomers, both at ESO Headquarters and at the Observatory in Chile. Their role has often been decisive in determining the success of the projects. It is impossible to acknowledge their contribution individually here.

It is equally impossible to give the corresponding list of people from the institutes in the ESO member states who provided unique expertise and supplied fully working instruments. The names of external PIs and Co-PIs of the instruments in Tables 1, 2 and 3 are just a reminder of the massive external contribution to instrumentation. The full list of those involved with their responsibility in the different projects can be found in the publications quoted in the ESO instrument pages.

Finally, I would like to mention the key role of A. Moorwood, with whom I shared 30 years of ESO instrumentation activities, working under five Directors General, and to thank A. Glindemann, J. L. Lizon and L. Pasquini for supplying their unique knowledge for this article. The publication statistics are from the public ESO Telescope Bibliography, maintained by the ESO Library.

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Links

[1] Convention and Protocols, European Southern Observatory (January 1987): https://www.eso.org/public/archives/books/pdf/book_0017.pdf

Notes

[a] EFOSC2 was at the 2.2-metre telescope from 1991 to 1997, at the 3.6-metre telescope from 1998 to 2007 and at the NTT from 2008.
[b] The following La Silla instruments were built by consortia in collaboration with ESO. Some more information about their teams is listed below:
- TIMMI2: PI H. G. Reimann (Germany), Co-PIs H.-U. Käufl (ESO) and H. Hron (Austria).
- HARPS: PI M. Mayor (Switzerland), Co-PIs W. Benz (Switzerland), J. P. Sivan (France) and L. Pasquini (ESO).
- WFI: PI K. Meisenheimer (Germany), Co-PIs M. Capaccioli (Italy) and D. Baade (ESO).
- FEROS: PI B. Wolf (Germany), Co-PIs J. Andersen (Denmark), A. Kaufer (Germany) and L. Pasquini (ESO).

[c] FEROS was at the 1.52-metre telescope between 1999 and 2002.
[d] The 2.2-metre telescope was installed on long-term loan from the Max-Planck-Gesellschaft and has not been offered for time at ESO since 2014.
[e] CRIRES has not been offered to the community between 2014 and 2018 because of an upgrade project.


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The VLT/I at sunset.

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End-to-End Operations in the ELT Era

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The Data Flow System is the infrastructure on which Very Large Telescope (VLT) observations are performed at the Observatory, before and after the observations themselves take place. Since its original conception in the late 1990s, it has evolved to accommodate new observing modes and new instruments on La Silla and Paranal. Several updates and upgrades are needed to overcome its obsolescence and to integrate requirements from the new instruments from the community and, of course, from ESO's Extremely Large Telescope (ELT), which will be integrated into Paranal's operations. We describe the end-to-end operations and the resulting roadmap guiding their further development.

The origins

At the time of the construction of the VLT in the late 1990s, it was already becoming clear that the "classical observing cycle of trekking to the telescope and returning home with a tape of unprocessed data", as Quinn (1996) described it, was no longer the most efficient way to deal with the coming generation of 8- to 10-metre telescopes. The first paradigm change introduced by ESO was Service Mode (SM), in which pre-defined observations are executed when the observing conditions match those needed for the specific science case. The second was to guarantee the calibration of the instruments to a pre-defined level of accuracy and to allow archive science, implying a well-defined calibration plan and continuous quality control of the calibration process. Quinn also noted that a direct consequence of this was that the "flow of data must be managed from start to end of the observation process", resulting in the development of the Data Flow System (DFS; Quinn 1996). It was designed between 1994 and 1995, and deployed on the NTT between 1996 and 1997 during the "NTT Big Bang", when that telescope was overhauled to become a prototype of the new VLT standard.

The main building blocks of the DFS were already implemented at that time as a series of interconnected but standalone processes and tools: proposal handling; observation handling; maintaining the science archive; and data processing pipelines. One of the key concepts at the core of the original DFS was the Observation Block (OB), the quantum unit that defines all the information required to execute an independent set of observations on a specific target. Over time, the system has become more complex as new types of observing programmes have been added, including new modes and new concepts on top of the individual OBs (for example, containers in the ESO Public Surveys). Many tools underwent substantial changes and upgrades to cope with these new concepts and technical requirements, while others grew more organically.

The DFS gradually evolved to reach the current implementation (Figure 1). The core concepts of the system are robust (for example, the quantum unit of the OB to define observations) and a set of interfaces ties the tools together. Nevertheless, in many areas the tools have grown beyond a level at which they can be efficiently maintained, are based on aging technologies, and/or don't take advantage of new technical capabilities. Furthermore, the original concept of data flow has been broadened to include not only the data themselves, but also the whole operation process, from the original proposal for observing time to the distribution of science-ready data packages — i.e., an "end-to-end operations" process. Last, but not least, ESO is building the ELT, and one of its top-level requirements is that its operations must be fully integrated with Paranal.

The time has come for an in-depth review of ESO's Data Flow System, and a (r)evolution.

Evaluation of the end-to-end process

In addition to being the backbone of the operations of about 20 instruments on 12 telescopes over two sites, the DFS provides a rather homogenous interface for users (including both the community and internal users). The system must be sufficiently versatile and flexible to cope with this complexity and to incorporate new and continuously evolving instruments. In particular, the DFS will have to efficiently support ELT operations. Furthermore, sub-processes and the corresponding tools must pass information from one stage to the next one effectively, avoiding duplication and averting inconsistencies.

Besides these top-level requirements, the evaluation of the DFS incorporates the ELT top-level requirements, and the requirements derived from the future instruments (in particular from the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations [ESPRESSO], the 4-metre Multi-Object Spectroscopic Telescope [4MOST] and the Multi Object Optical and Near-infrared Spectrograph [MOONS]). It also includes the results of a review of the current system, summarised in a series of Messenger articles (Primas et al., 2014 for SM; Romaniello et al., 2015 for the Archive, Arnaboldi et al., 2014 for Phase 3; Sterzik et al., 2015 and Patat et al., 2017 for scientific return). The feedback from the community has been assimilated through the ESO2020 workshop and poll (Primas et al., 2015) and the recommendations of the ESO2020 Time Allocation and Science Data Management working groups, as well as input from ESO's advisory bodies: the Scientific Technical Committee and the Users Committee.

The tools and facilities offered in other observatories were also examined to estimate the evolving astronomical environment and the possibility for their re-use in ESO's tools. Finally, the need to ensure that the DFS could be maintained over an expected lifetime on the order of 20 years guided any technological choices.

All the new requirements were assessed; while some are indeed novel, they are all compatible with the current fundamental concepts — even if not with the current

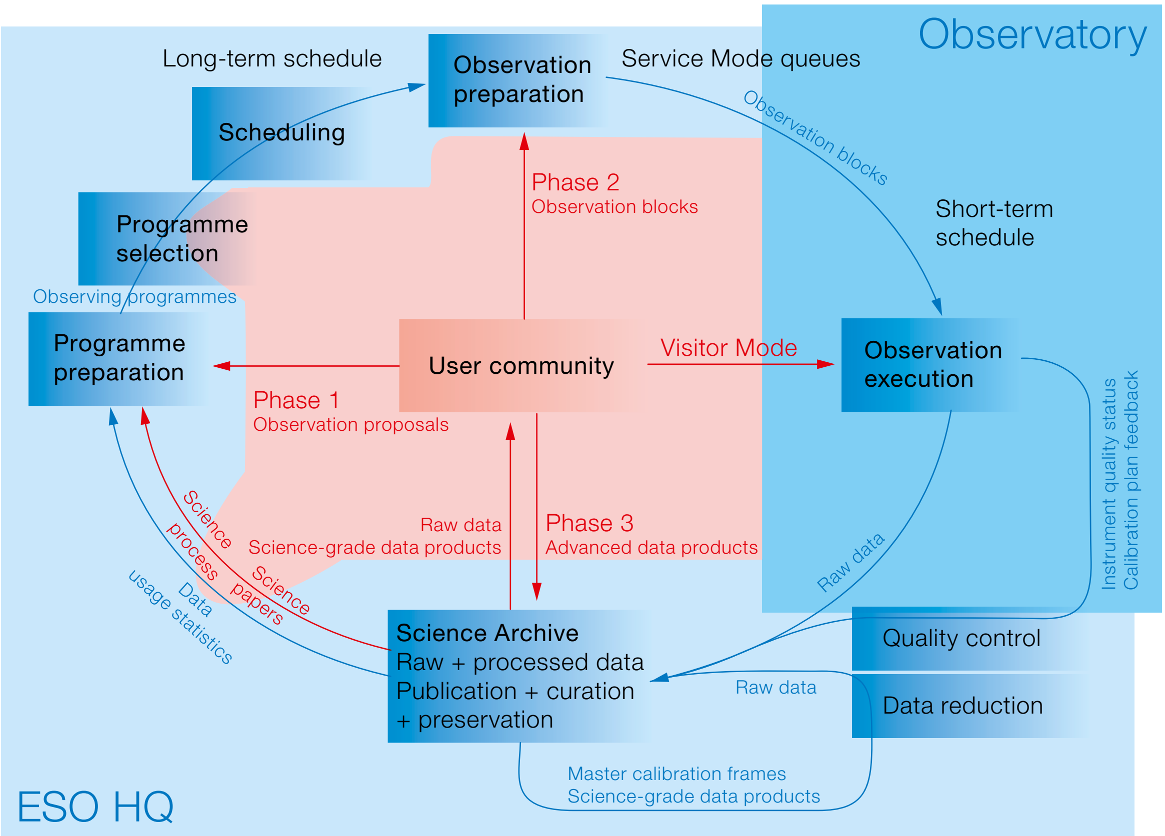

Figure 1. End-to-end operation process: the main sub-processes are indicated in boxes; the background colour indicates the main actors involved in each step. The arrows are labelled with the information flowing over them. This "DFS Wheel" is an adaptation of the original one presented by Quinn (1996). While the overall process will not change much over the deployment of the upgrades described in this roadmap, many of the sub-processes and the tools implementing them will undergo in-depth, and often complete, re-implementation.

tools — implying that the overall end-to-end operations, which has been in use since the start of VLT operations, is still sound. What is needed is an in-depth "clean-up" and update of the system rather than a complete re-engineering. As no exotic or extreme new requirement was identified, we did not investigate different operation schemes in detail. The new end-to-end operations model will be a modernisation of the current one, building on the many years of experience operating the VLT and, before that, La Silla.

All sub-processes were assessed, and areas requiring work were identified. An overall high-level plan was designed and broken down into individual projects. The dependencies between these projects were accounted for, together with specific milestones (for example, the first light of a given instrument) as well as the savings that they will generate in terms of maintenance and operations. The resources in time, equipment and staffing were evaluated for each project. Some of these projects were ongoing at the time of this exercise, so they were already collecting requirements and evaluating costs. Others will take place in several years' time; these have been estimated from the complexity of the existing system and the additional requirements. The preliminary estimates will be refined when the projects actually start — in the meantime they are sufficient for planning the roadmap presented here.

In the following section, we offer an overview of these projects and, by way of illustration, delve into some of them in more detail.

Roadmap towards a new data flow system

Platform

Breaking with a long tradition of requiring users to install and deploy programs on their own computers, new tools are being developed using application programming interfaces (APIs) to services hosted at ESO. Web-based user interfaces and user- or science case-specific scripts and even desktop applications can be built against these APIs. The strict separation of user interface and business logic has enormous advantages in terms of maintainability. Rather than asking users to download and install new software versions ESO can seamlessly fix bugs and roll out new features by deploying new software to an ESO server for immediate availability to all users.

The paradigm chosen is the representational state transfer (REST), an industry standard that the contracted software engineers are familiar with. Additionally, there are now powerful web frameworks that enable fast development of powerful, large-scale user interfaces. The framework chosen is Google's Angular 5. User interfaces tend to age faster than the underlying business logic. Thanks to their separation, interfaces can be updated without requiring a re-implementation of the business logic. Also, as the APIs are exposed (and documented), power users can access them directly using scripts to execute series of commands that would be cumbersome from a web interface; indeed, users can even develop their own custom interfaces.

Before the observations

Phase 1 includes the release of details of what is being offered in a particular observing cycle through a Call for Proposals, the preparation of proposals for observing time by the community, the handling of these proposals, and the organisation of and support to the Observing Programme Committee (OPC), which reviews the observing proposals submitted. The Principal Investigators (PIs) and co-investigators (Co-Is) of successful proposals then prepare the detailed specifications of their observations — the OBs — during Phase 2. Both Phase 1 and Phase 2 activities are supported by exposure time calculators (ETCs).

Following the plan, all tools related to Phase 1 and 2 and the ETCs will be modernised through the implementation of REST APIs and web interfaces. These projects have started and are at different stages of implementation.

Phase 2

For operational reasons, the Phase 2 systems were the first to be upgraded. They had already been updated to support survey operations on the Visible and Infrared Survey Telescope for Astronomy (VISTA) and the VLT Survey Telescope (VST) in 2010 and 2011, with the addition of scheduling containers. However, it was already recognised in 2014 that the current system would not be able to respond to the requirements from ESPRESSO's planet-hunting strategy and massive spectroscopic surveys with 4MOST. The Java desktop application called P2PP (Phase 2 Proposal Preparation) was introduced in 1997, replacing the original Tcl/Tk application. It is now being replaced by the new API-based P2[1], which reproduces its functionalities while adding new ones. With P2, the user creates OBs and stores them directly on the Garching repository. A bi-directional database replication ensures that the OB's content is the same in both the Garching and the Paranal repositories.

The P2 project was started in 2016; the P2 web tool and the matching visitor Observing Tool (vOT version 4) have been deployed for Visitor Mode support during 2017. The deployment for Service Mode will be done in two phases in 2018, first on Unit Telescope 2 (UT2) and on the survey telescopes for Period 101, followed by implementation on all Paranal telescopes for Service Mode for P102. A second wave of developments that will include specific VLTI and Adaptive Optics operational requirements, enable definition of complex observing strategies through nested scheduling containers, and also enable more streamlined connections with the Phase 1 ETCs will take place in 2019. The inclusion of the La Silla operations in the new P2 system will take place in 2018-2019, in time for the new instruments NIRPS and SOX. Once this is done, we will be able to decommission the legacy P2PP and underlying servers.

Phase 1

The Phase 1 support tools include the long-lived ESOFORM, a LaTeX package that has been used to define proposals for observing time since Period 60 (we are now in Period 100). However, the ESOFORM is only the tip of the iceberg of Phase 1 tools. A series of tools process the LaTeX files of the observing proposals and store some of the information in a database (unfortunately the LaTeX format means that some important information cannot be stored in such a way that can be easily retrieved programmatically), deal with the administration of the OPC and the OPC reviewer rankings and recommendations, interface with the scheduling system, and finally handle the communication to the proposers.

The maintenance of these tools has become cumbersome, and integrating new requirements (for example, the recommendations from the ESO2020 Time Allocation working group) would be impractical. These tools and the underlying databases have grown organically. In terms of technology and architecture, they require a complete redesign and implementation. Because of the tight integration of all of the Phase 1-related subsystems, and because of the fundamental changes in the underlying infrastructure, the change from the old to the new system can only take place when the whole system is ready.

Currently, the first two modules — which define what is offered in an observing cycle and how to define and submit proposals — are under development and are expected to be delivered in the first half of 2018. The next modules (OPC administration, handling OPC rankings, interactions with the submitters) will be developed in 2018 and 2019. The overall integration will take place in 2020 and we expect to have the new system in place by the end of 2020. While it would be nice to deploy the new proposal submission system earlier, its deeply rooted interconnections with the rest of the Phase 1 infrastructure make that impossible. From the user point of view, the proposal submission will be fully web-based, supporting collaborative work from the PI and Co-Is. Figure 2 shows screenshots of the P1 and P2 web user interfaces.

Exposure time calculators (ETCs)

The ETCs are already web-based, but implemented in a way that precludes easy interaction via scripts (or from other tools like Phase 1 and Phase 2 preparation) and that uses specific models for the instruments. This makes their maintenance cumbersome and their integration and use in batch mode difficult. The ETC upgrade project was initiated in 2017 and will likely be completed by 2020. Some features of the user interfaces at other observatories, such as the possibility to save and share ETC sessions, are included in the requirements. Thanks to the modular structure of the ETCs, the benefits of the new system will appear gradually on the ETC web pages.

The new P1, P2 and ETC systems share exactly the same authoritative instrument definition model as that used for the instrument itself (i.e., the Instrument Packages), ensuring consistency between the tools. The tools will also be able to interact and exchange information using their APIs. This will make a tight integration possible between the ETCs and the P1 and P2 systems; all the calculations performed to estimate the telescope time required for a Phase 1 proposal are preserved in the proposal itself, and will be available as the basis on which to optimise the observing strategies at Phase 2. The ETC API will also make simulations available for Quality Control processes (see the After the observations

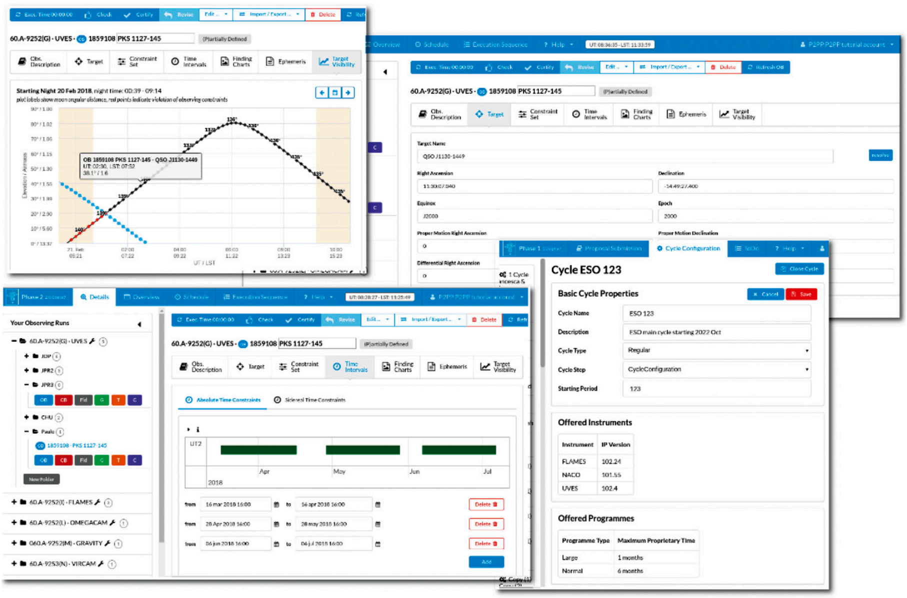

Figure 2. Screenshot of the P1 and P2 web tools developed to prepare proposals and observations.

section), and to investigators who want to explore a broad range of parameters or apply a simulation to a catalogue of objects.

Towards a unified GuideCam tool

OBs for several instruments must include very specific details on the instrument configuration (for example, fibre positions on a multi-object spectrograph). These are currently defined using a suite of auxiliary preparation tools (for example, FORS Instrument Mask Simulator [FIMS], KMOS ARM Allocator [KARMA]), many of which are based on the increasingly outdated Tcl/Tk technology. As these tools are too complex for implementation in current web technologies, we developed a platform and implemented it as a plug-in to the Aladin sky atlas tool[2]. This becomes the basis for all future observation preparation tools. This new tool, GuideCam[3], is already available for various instruments (Figure 3). Existing preparation tools for other instruments that will not be decommissioned in the foreseeable future will be retrofitted to GuideCam over the coming years. In 2018, GuideCam will also include a generic system to produce finding charts, to replace the aged SkyCat tool; this will make it much simpler to prepare Service-Mode-compliant finding charts. Furthermore, thanks to the integration between GuideCam and the P2 system, information will be embedded in finding charts and will be available to the staff reviewing and executing the observations.

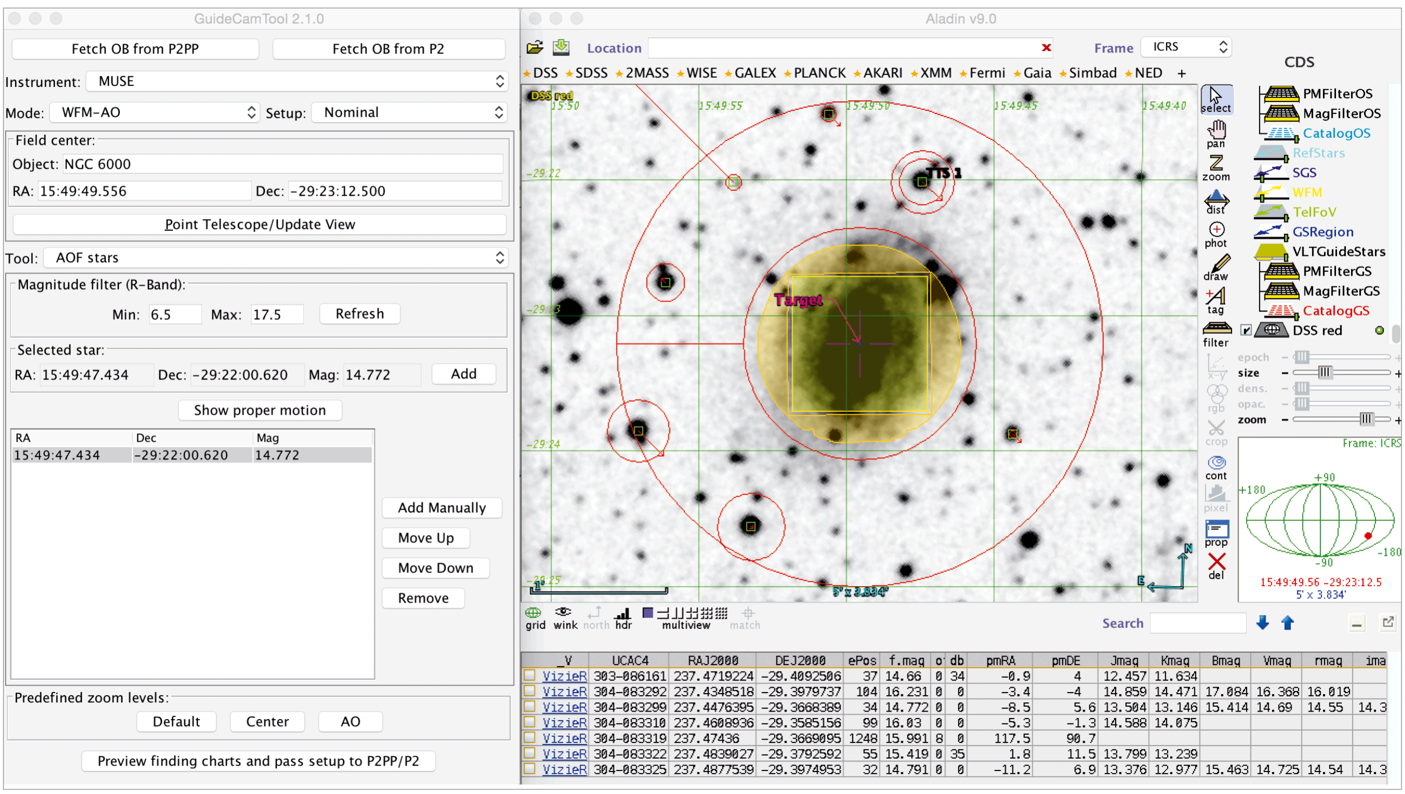

Figure 3. Screenshot of the Unified GuideCam Tool.

Scheduling the observations

Long-term telescope schedules are assembled by accounting for a number of factors, including the ranking of Phase 1 proposals by the OPC, ESO high-level science operation policies[4] and any constraints specified in the proposals themselves — both deterministic (for example, target coordinates and the phase of the Moon) and statistical (such as image quality). The output of the new P1 system will enable a much finer granular accounting of the constraints and geometry than the current system, ensuring that all of the information relevant for scheduling and observations execution is fully captured.

The scheduling tool that is currently deployed treats VLT units separately and the only case requiring coordinated allocations on multiple Unit Telescopes (i.e., the VLTI) has been managed manually, within pre-allocated slots. The start of ESPRESSO operations, with its capability of operating in Service Mode at any UT during the night, poses a new challenge, which can only be addressed by a parallel approach to VLT scheduling. This requires a radical change to the scheduling paradigm.

Therefore, we also plan to update the current Telescope allocation Tool (TaToo). The new scheduling tool will enable complex strategies, such as simultaneous or sequential scheduling on multiple telescopes, therefore addressing operational requirements for ESPRESSO. This project is expected to start in early 2019, once the later phases of the P1 project are underway.

Observations

Observations on the mountain are either performed in Visitor Mode, for which the observer travels to La Silla or Paranal to execute and fine-tune their observations in real time, or in Service Mode. For a Service Mode run, the observer selects the observation to be performed from the pool of Phase 2 OBs, executes it and evaluates its success based on fulfilment of predefined observing parameters. The selection of the "best" OB for execution is assisted by the Short-Term Scheduler (STS), also called the OB Ranking Engine (ORANG), which accounts for policies and user-specified priorities, as well as for the prevailing conditions. ORANG also takes into account additional constraints such as time criticality and links between OBs in OB containers. However, ORANG has no capabilities to account for the evolution of the observing conditions. We are working with the Paranal astro-weather group to integrate information provided by the Astronomical Site Monitor that goes beyond established weather parameters such as cloud transparency and seeing, including water vapour pressure, turbulence profile, etc.

Furthermore, ESO has embarked on several investigations with weather forecasting institutions (both academic and commercial) to refine the existing forecast to suit astronomical needs. The goal is to be able to forecast the main parameters that are relevant to the observations — and, even more importantly, how they change — with a precision that can assist in the selection of future OBs. We will likely review and upgrade the STS to account for astro-weather forecasts, with the ultimate goal of forecasting the seeing conditions and the turbulence profile, as these are particularly critical for the operation of the AO-assisted instruments — especially on the ELT. In parallel with this functional upgrade, a complete re-implementation of the underlying Observation Tool (OT) is required by its outdated code base. While the preliminary studies are already ongoing, the project itself will be launched only in 2020; we hope to have the astro-weather forecast module in place in 2022, and the full OT/STS deployed in 2023.

In addition to these visible changes, a series of behind-the-scenes projects need to take place. For instance, the Data Handling System (which moves data between workstations at the Observatory before bringing them to the Science Archive) has been maintained since its creation, but has never been re-evaluated at the overall process level. The integration of the requirements from the ELT, as well as from the Quality Control project (see below) is a good opportunity. This will take place in parallel with the implementation of the interfaces to the ELT between 2021 and 2023, including both "front end" (from the DFS to the ELT control system) and "back end" (from the ELT back to the DFS).

After the observations

Science Archive

The Science Archive System has always been considered the final repository of VLT data, thus preserving their legacy value. Over time, its role has become more and more central in overall operations. Thanks to advances in the internet, its role now also includes the distribution of data to both the original PI as well as to other independent archive researchers. Teams leading Public Surveys and Large Programmes deliver large, consistent, science-ready datasets called the External Data Products to the Archive via the Phase 3 process (Arnaboldi et al., 2014). In parallel, the development of science-grade pipelines has enabled ESO to systematically process the data from a (growing) number of instruments, creating the Internal Data Products (Romaniello et al., 2016). Both raw data and science-grade data products are very popular with the community, with the number of users and the request rate steadily increasing (Romaniello et al., 2016).

However, the core archive services — the ensemble of web interfaces and underlying system — have not evolved much since their deployment in the late 1990s, while web and database technologies have flourished and the Virtual Observatory (VO) protocols have matured. A project to re-implement the Archive Services is underway. Its goal is to let the users search for and discover ESO data, taking advantage of the detailed and consistent metadata describing them, either through an interactive web interface, or through a VO-compliant API for more complex queries. The API will also open the archive to the available VO tools (for example, Aladin, TopCat, etc). Finally, the Archive will offer previews of its assets, allowing users to quickly evaluate the suitability of a file for their purposes. The previews include progressive multi-scale images (c.f. Google Earth), which will be broadcast via the HiPS network[5]. Thanks to this, services like ESASky[6], which gives access to a highly curated subset of multi-wavelength/multi-observatory data, will also be able to access, display and retrieve suitable ESO data – for instance, data products from large surveys. The first release of this new Archive Service, which will include most of the data products, is scheduled around the time of publication of the present article and will be described in detail in the next issue of the Messenger.

Quality control (QC)

One of the key concepts of the original DFS was the introduction of a formal calibration plan ensuring that instruments can be calibrated to a pre-defined accuracy; the operations plan ensures that all the required ancillary frames are acquired and the quality control (QC) system verifies their validity and suitability through instrument health and trending parameters. A QC infrastructure has been developed over the years to monitor the instruments and detect deviations from their specifications before the instrument performance significantly degrades. The QC also produces certified calibration frames, which are stored in the Archive and can be used by the pipelines for the science data processing.

This infrastructure is robust and flexible, but uses a technology that has issues in terms of maintainability. Furthermore, we are now in a situation where the scope of QC can be expanded beyond the calibration and instrument stability. A QC infrastructure can be deployed directly at the telescope, together with the online pipelines, to provide a systematic real-time assessment of many parameters of the data as it is acquired. This will help to evaluate observations from new complex instruments, for which raw data are so entangled that an inspection of raw frames would not be sufficient to judge their quality (for example, integral field units and interferometric instruments). Furthermore, the pipeline generation of science-grade processed data implies that the data quality is also evaluated in a systematic way. Finally, the traditional instrument calibration QC produces parameters that can be compared directly with the output of the instrument simulators, closing the loop between the ETCs and the actual instrument. Thanks to the ETC API, deviations between the simulation and the measurement can result in flagging a problem, or in updating the ETC parameters. This major evolution of the QC processes constitutes a significant effort and the project is due to start in mid-2018, with new QC systems deployed gradually until 2022.

Data processing and pipelines infrastructure

The QC system, the online pipelines (at Paranal) and offline pipelines (on users' machines) rely on a series of data organisation tools (for example, to select and associate suitable calibration files) and data processing infrastructure that calls and manages pipeline recipes (for instance, ESOrex, and the workflow system Reflex). The pipeline recipes themselves are implemented using the low-level Common Pipeline Library, and more advanced algorithms from the High-level Data Reduction Library. The suitability of these tools will be reviewed in the coming years accounting for new internal and community requirements (for example, interfacing with Python) and new capabilities (for example, cloud computing). The outcome of this review will lead to an evolution of pipeline systems and their infrastructure. Whilst the scope and nature of this project are not defined yet, resources have been earmarked between 2020 and 2021.

Infrastructure

The DFS relies on a series of infrastructures, which must be maintained and allowed to evolve. A couple of examples are given below.

The first is the Next Generation Archive System (NGAS), the storage technology developed for the Science Archive. NGAS has evolved over the past decade, and is now, either directly or indirectly, used at ESO, ALMA and other institutions. As storage technologies evolve rapidly, NGAS must also follow.

The DFS also depends on many databases; while our demands are fairly modest by modern standards, we have original requirements (such as our multi-site architecture, or the spherical geometry of the celestial sphere), which are not fully supported by out-of-the-box products. Furthermore, the landscape of available database systems is evolving in terms of capabilities, support and cost.

Conclusions

An ambitious roadmap has been developed to overhaul the dataflow system supporting the VLT observations, the ultimate aim being to accommodate the requirements of ELT and new VLT instruments, and to ensure the system's future maintainability. This plan has been developed and endorsed internally at ESO. An external review is taking place to ensure its completeness, review its soundness and evaluate synergies with similar developments at other observatories. The developments are being staged to maximise the use of finite resources, while meeting deadlines. One of the main goals is to integrate all of the sub-processes and make the overall end-to-end operations seamless, both for the users and for the operators. While many new tools and systems will be deployed as soon as they become available, some require major infrastructure changes and must therefore be completed before they can enter operations. The ultimate deadline for this series of projects is ELT first light.

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[2] Aladin sky atlas: aladin.u-strasbg.fr
[3] The unified GUideCam Tool: www.eso.org/sci/observing/phase2/SMGuidelines/GUCT.generic.html
[4] VLT/VLTI Science Operations Policy: eso.org/sci/observing/policies/Cou996-rev.pdf
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[6] ESASky: sky.esa.int

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The VLTI Roadmap

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ESO's Very Large Telescope Interferometer (VLTI) was a unique facility when it was conceived more than 30 years ago, and it remains competitive today in the field of milli-arcsecond angular resolution astronomy. Over the past decade, while the VLTI matured into an operationally efficient facility, it became limited by its first-generation instruments. As the second generation of VLTI instrumentation achieves first light, further developments for this unique facility are being planned and are described here.

Introduction

The VLTI will remain — even in the era of ESO's Extremely Large Telescope (ELT) and the Atacama Large Millimeter/submillimeter Array (ALMA) — the European facility with the highest angular resolution. The past decade has seen ESO master the difficulties of coherent combination of an optical array with four Unit Telescopes (UTs) or Auxiliary Telescopes (ATs). These successes paved the way for the ambitious second-generation instruments: GRAVITY (GRAVITY Collaboration, 2017a,b) and the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE) (see Matter et al., 2016; Lopez et al., 2014). Additionally, the VLTI facility itself has been upgraded to accommodate the new instruments, bringing improvements in both operation and performance (Woillez et al., 2016; Gonté et al., 2016).

With the VLTI and ALMA, ESO users have now gained access to milli-arcsecond astronomy from the near infrared to the millimetre regimes. Since its inception, the VLTI has pursued two goals: delivering an imaging capability at the milli-arcsecond resolution level and providing precise relative astrometry with a goal of ten micro-arcseconds precision, the latter being a much bigger technical challenge.

The scientific production of the VLTI has been vastly dominated by relatively simple but important morphological measurements of the near and mid-infrared emission of bright sources and spectroscopy with milli-arcsecond angular resolution. These reconstructed images have challenged a number of established theories in the field of stellar physics and active galactic nuclei (AGN). With these images, the VLTI can now reveal the true underlying complexity of these objects.

The VLTI offers the possibility of spatially and spectroscopically resolving a range of time-variable astrophysical processes that cannot be accessed via other techniques. It is a tool to challenge our indirect understanding of stars, explore rotation, pulsation, convection, shocks, winds, accretion, and ejection phenomena as they happen and reveal the complex interplay between a star and its environment throughout its lifetime. The capability of the VLTI to resolve the complexity of AGN, to precisely measure the central black hole mass and to pinpoint its distance with unmatched accuracy has not yet been exploited. With GRAVITY, the VLTI has become an astrometric machine, offering a unique way to observe strong gravity in action and explore physical conditions close to the horizon of the black hole at the Galactic Centre. As such, it offers a rare opportunity for ground-based astronomy to probe the nature of gravity and contribute to the field of fundamental physics. The technology required to enable such an ambitious goal will most probably open the way for more science projects exploiting micro-arcsecond astrometric capability from the ground. The powerful combination of fascinating science cases and instrumental innovation is a strong incentive to support the further development of the VLTI.

The evolution of VLTI infrastructure and the associated increase in performance should bring trust in our ability to continue developing milli-arcsecond astronomy from the ground. Whether it will be by expanding the VLTI or by developing other facilities has yet to be established.

Challenges

ESO has surmounted the difficulties associated with optical coherent combination and the VLTI is now entering a consolidation phase. The next challenge is to combine increased sensitivity and precision. The next step is phasing (also called fringe tracking) of the array of telescopes on-axis and, at a later stage, off-axis. This will considerably improve the accessible sizes of the samples and will enable high-resolution spectroscopy. As previous experience — using the Astronomical Multi-BEam combineR with the Fringe-tracking Instrument of NIce and TOrino (AMBER+FINITO) and the MID-infrared Interferometric instrument with the Fringe Sensor Unit (MIDI+FSU) — suggests, efficient phasing requires the implementation of a number of subsystems or upgrades, as well as a particular attention to global performance, including particularly good wavefront correction in the UT and AT arrays. ESO has developed sufficient expertise to tackle this crucial step for MATISSE, which cannot deliver its full potential without phasing. The dedicated project called GRAVITY for MATISSE (GRA4MAT) is using GRAVITY's own fringe tracker to phase MATISSE, and is expected to come to fruition in 2019.

The second challenge is to bring GRAVITY up to its ultimate astrometric performance. This remarkable scientific outcome will be delivered thanks to a significant technological and system effort. Early results indicate that the short-term astrometric precision is of the order of 50 micro-arcseconds (GRAVITY Collaboration, 2017a,b), but the final accuracy long-term (over a timescale of months) still needs to be assessed.

The third challenge is to democratise access to the VLTI by providing user assistance to help with observation preparation, data reduction and image reconstruction. The VLTI community has made considerable progress in this direction, for example, through the development of reliable software and by running dedicated training schools. However, as revealed through polling of the ESO Users Committee, handling VLTI data is still perceived as an expert-only activity. ESO is addressing this by streamlining the process of preparing VLTI programmes, with the goal of shielding users from the complexity inherent in earlier VLTI operations, when combiners used only two or three telescopes and telescope configurations were restrictive.

The VLTI benefits from a particularly active and dedicated community. Both ESO and the VLTI community should explore a comprehensive interface that provides users with easier access to data reduction and image reconstruction. Without a doubt, expanding the user community will bring new ideas for the scientific exploitation of the VLTI. Between 2004 and 2017, nearly 350 individual Principal Investigators (PIs) applied for VLTI time. As with any facility, the broadening of the user base also comes when new capabilities are offered; the first few semesters over which GRAVITY has been offered have brought almost 25 PIs who had never used the VLTI before.

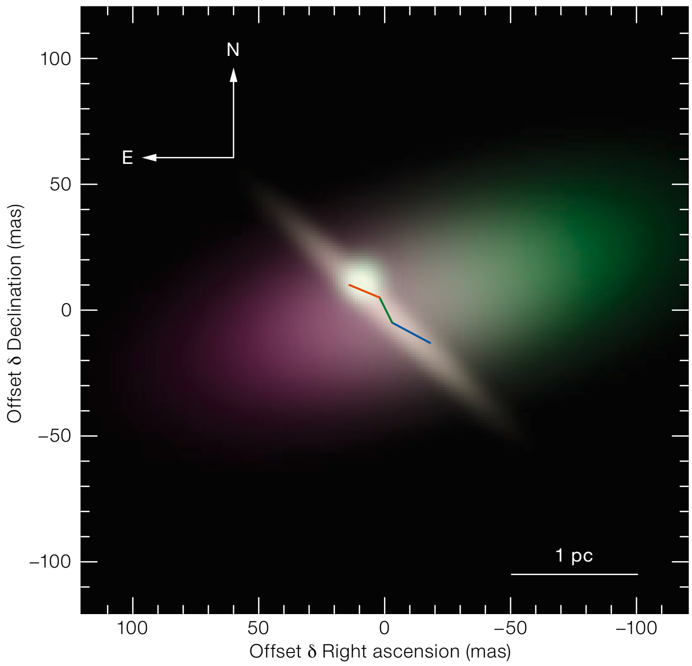

Figure 1. Three-component model of the dusty environment in the Circinus galaxy based on MIDI observations (Tristram et al., 2014). Red, green and blue correspond to wavelengths of 13 μm, 10.5 μm and 8.0 μm, respectively. Despite their low surface brightness, polar outflows account for 80 % of the mid-infrared flux in this synthetic image. The water maser disc is deduced from centimetre Very Long Baseline Interferometric (VLBI) observations. Reproduced with permission of K. Tristram.

Key scientific questions for VLTI second-generation instruments

During the next decade, the second generation of VLTI instruments — GRAVITY, MATISSE, and to a certain extent, the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER) — are expected to contribute to many astrophysical domains. We explore a few of the important ones here.

The inner parsec of Active Galactic Nuclei

GRAVITY and MATISSE are both expected to contribute to the study of AGN. Historically, VLTI observations of AGN have been limited to a handful in the *K*-band by VINCI (Wittkowski et al., 2004) or AMBER (Weigelt et al., 2012). MIDI has observed several AGN in the *N*-band but the results are puzzling because they imply that most of the mid-infrared emission comes from the polar regions, not the dusty torus as expected (Hönig, 2016). Since MIDI was limited to a single baseline, effective imaging of AGN was not possible.

MATISSE will provide snapshot imaging of AGN, allowing a much more detailed view of the morphology of the dust in the central parsec of galaxies hosting AGN, thereby possibly ruling out the simple dusty torus model, as MIDI observations seemed to imply (Tristram et al., 2014; see Figure 1). GRAVITY is also expected to contribute to the study of AGN, as it has greater sensitivity than AMBER, particularly in its spectrally resolved mode using the fringe tracker. The gas in the inner regions of AGN produces a so-called broad line region that can be imaged directly by GRAVITY. So far, the only way to study the broad line region has been to use reverberation mapping, which requires months of photometric monitoring. The VLTI can directly resolve the size of the broad line region, and early observations with GRAVITY as well as pioneering work on AMBER indicate that broad line regions are more likely to be compact than originally estimated by reverberation mapping studies (GRAVITY Collaboration, 2017; Pribulla et al., 2011).

Strong gravity in the Galactic Centre

The VLTI instrument GRAVITY has been designed to observe the Galactic Centre. The unprecedented angular resolution of the VLTI will help to address several questions. The first goal is to measure the effects of General Relativity as the star S2 undergoes peribothron in 2018 — i.e., the point in its elliptical orbit at which it is closest to the supermassive black hole Sgr A*. Another goal is to understand the origin of the Sgr A* flares which occur daily. GRAVITY will help to discriminate between different scenarios, for example, disc accretion events, accretion of stars, and fluctuations in a jet. Early results are very promising and call for long-term monitoring of the Galactic Centre (GRAVITY Collaboration, 2017a).

Binarity across the Hertzsprung Russell diagram

Increasingly, multiplicity is believed to play a fundamental role in stellar evolution and stellar dynamics. An example of the fundamental contribution of the VLTI is the definitive evidence that massive main sequence stars are all in multiple systems (Sana et al., 2014). The contribution to high angular resolution imaging is not limited to binary statistics and also probes massive star binaries (Figure 2). Other classes of stars are yet to be studied to determine their multiplicity fractions; the VLTI could be used to conduct surveys of statistically complete samples of stars with different spectral types.

The VLTI is also frequently used to conduct in-depth studies over a range of binary systems, for example, the determination of independent distances and masses at the 1 % level using double-lined eclipsing binaries (Pribulla et al., 2011) and resolving wind-wind interactions in Luminous Blue Variables (Weigelt et al., 2016). GRAVITY, with its sensitivity and spectral coverage (encompassing the full *K*-band, a significant increase on the *K*-band coverage with AMBER) offers the unique capability of spectrally disentangling binaries. This was pioneered with AMBER and proved invaluable in modelling complex systems, such as the Wolf-Rayet γ2 Velorum (Lamberts et al., 2017).

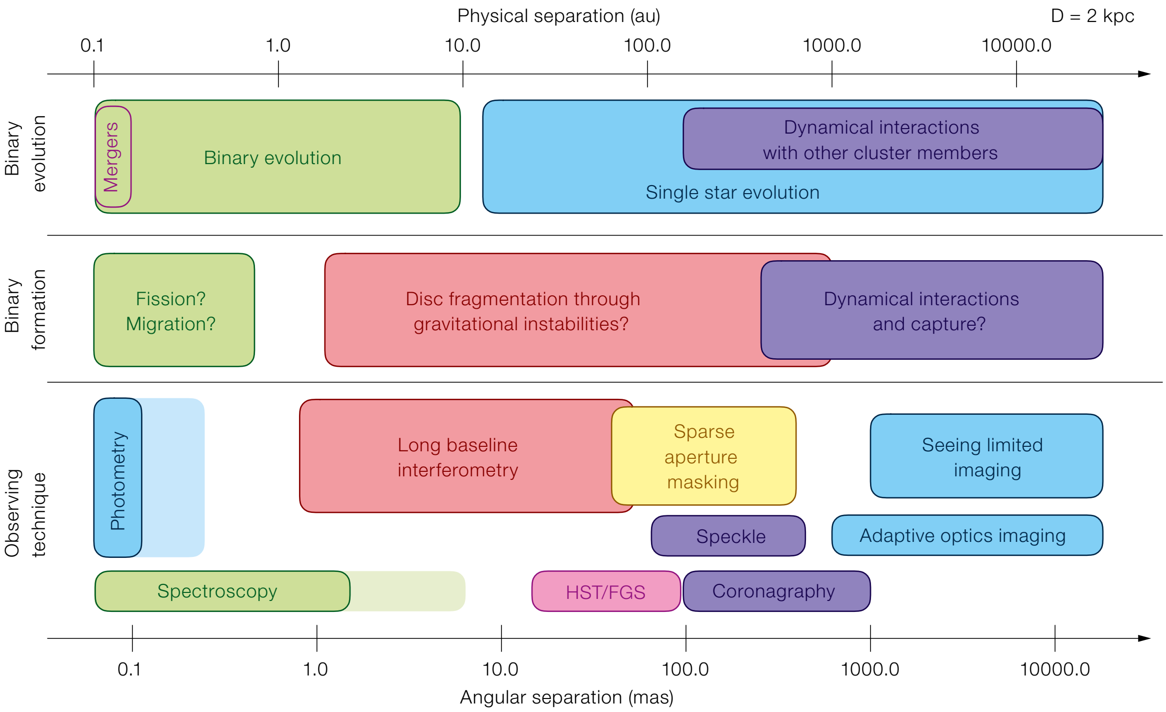

Figure 2. A schematic diagram to compare the angular scales associated with different observing techniques (bottom row), binary formation processes (middle row) and binary evolution (top row) for hot O-type stars at a typical distance of 2 kpc. This illustrates the unique role that the VLTI's long baseline interferometry can play in probing disc fragmentation in early systems. Thanks to its unsurpassed angular resolution, VLTI imaging is the only way to probe close binary systems that are interacting. Reproduced with permission of H. Sana.

During GRAVITY commissioning new phenomena were observed, including a micro quasar (Petrucci et al., 2017) in which relativistic jets could be resolved, and the accretion zone in a high-mass X-ray binary (Waisberg et al., 2017). High-precision interferometric instruments yield high dynamic ranges; PIONIER offers a detection limit up to a contrast of 500, which enables the measurement of dynamical masses of unexplored stellar classes, such as Cepheids (Gallenne et al., 2015). GRAVITY is expected to reach a similar dynamic range performance that, combined with its spectral resolution, will allow for a better characterisation of companions.

Mass loss from evolved stars

Evolved stars play a crucial role in enriching their host galaxies in heavy elements. Little is known about the actual mass loss mechanisms involved since all models underestimate mass loss rates. It is believed that mass loss is linked to pulsation, convection and/or shocks in the upper atmosphere of dusty stars (Höfner et al., 2018). The VLTI is uniquely positioned to resolve the photospheres and dust shells around evolved stars (Figure 3). The advent of 3D modelling and early imaging with optical interferometry suggest a strong departure from a symmetric central geometry, advocating for more advanced models than the typical 1D models and 1D morphological analysis of previous observations (Chiavassa et al., 2010).

PIONIER, GRAVITY and MATISSE are expected to continue targeting evolved stars, especially when all available wavebands (from *H*- to *N*-bands) are used simultaneously. An important obstacle to studying mass loss so far was that stars must be resolved both spatially and temporally in order to disentangle convection and pulsation, which have timescales of weeks. The availability of four-telescope observations offers the possibility of snapshot imaging on a timescale of a few days, which can reveal mass loss in all its spatial complexity, potentially tying dust patches above the atmosphere to phenomena at the surfaces of stars. PIONIER will resolve the photosphere, GRAVITY will probe the molecular wind and hot dust close to the sublimation temperature, and MATISSE will resolve the oxygen- and carbon-rich dust. ALMA can probe the larger-scale structure with H_2O and OH maser observations. SPHERE on the VLT could also provide complementary imaging, revealing interactions of the mass loss with the interstellar medium (Kervella et al., 2017; Figure 3).

Young stellar objects

Young stellar objects are among the targets of choice for the VLTI; the combination of high angular resolution (~ milli-arcseconds) and the spectral range (*H*- and *K*-bands) makes it the perfect machine to study the central regions of protoplanetary discs. For example, PIONIER recently revealed the universality of the truncated inner-ring structures in the hot dust discs of Herbig AeBe stars via a survey of 51 objects (Lazareff et al., 2017).

GRAVITY and MATISSE are expected to continue this legacy. GRAVITY offers the unique possibility of studying winds or jets thanks to its sensitive fringe tracker, which allows observations of Brγ, He I or CO lines at high spectral resolution (R ~ 4000). The gas and dust have very different dynamics in protoplanetary discs and play different roles in planet formation scenarios.

GRAVITY commissioning observations of S CrA revealed a Brγ emitting region of *r* ~ 0.06 au that was located in the inner gaseous disc but was twice as big as the truncation radius, tracing a wind (GRAVITY Collaboration, 2017c). Detailed modelling also indicates the presence of magnetospheric accretion. The sensitivity

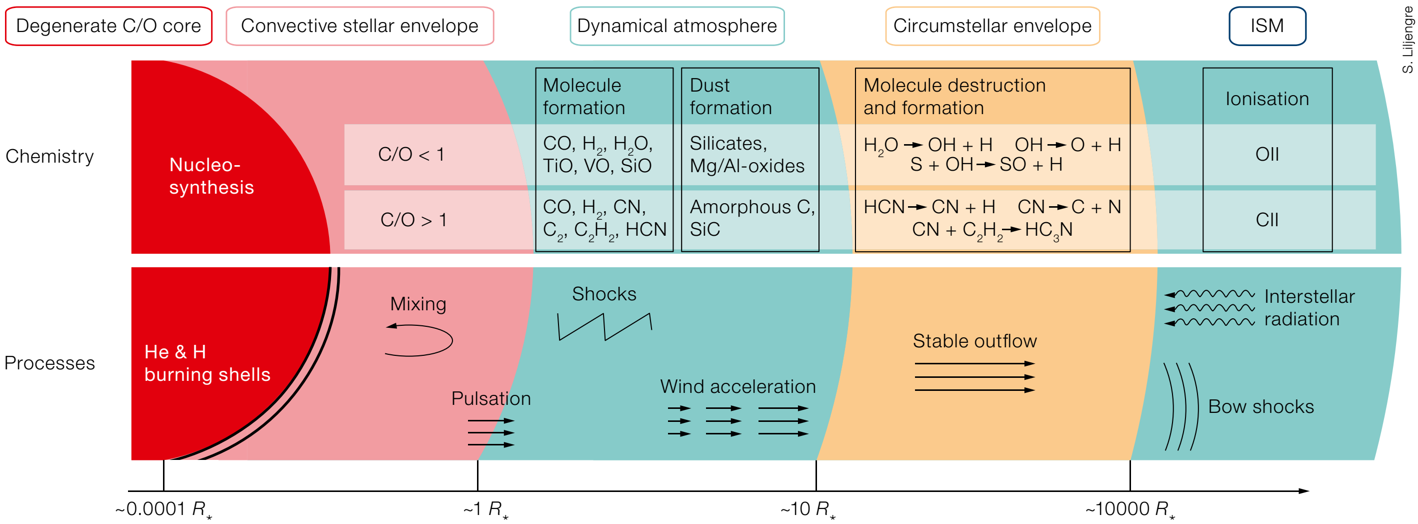

Figure 3. Schematic diagram of an asymptotic giant branch star from interior to circumstellar environment, showing the chemical and physical processes involved in mass loss. VLTI instrumentation (PIONIER, GRAVITY and MATISSE) can resolve these stars from their surfaces (at 1 R_*) to their circumstellar envelopes (out to ~ 10 R_*), probing convection, pulsation, shocks and dust formation. ALMA can resolve the circumstellar environment and molecular processes. VLT imaging at high angular resolution accesses the outer scales (100–1000 R_*). Reproduced here with permission of S. Lijengre.

of GRAVITY will allow this study to be extended further as the Brγ line can trace both the disc and the inner region of the stellar and/or disc wind. The availability of the full *K*-band will enable the study of the CO bandhead emission longward of 2.3 µm. The infrared CO emission traces warm gas in the inner regions of protoplanetary discs, potentially tracing the disc-star interactions (van der Plas et al., 2014; Illee et al., 2014).

MATISSE will continue mineralogy studies that MIDI initiated earlier, detecting different types of dust at different disc radii (van Boekel et al., 2004). MATISSE will provide much better insights into the morphology of the dust thanks to its four-telescope imaging capabilities, which will remove assumptions about the disc geometry. The VLTI will complement ALMA, which offers similar angular scales, to draw a complete picture of the dust and gas in protoplanetary discs (Figure 4).

Beyond GRAVITY and MATISSE

The need for milli-arcsecond resolution observations will not disappear once GRAVITY and MATISSE yield their

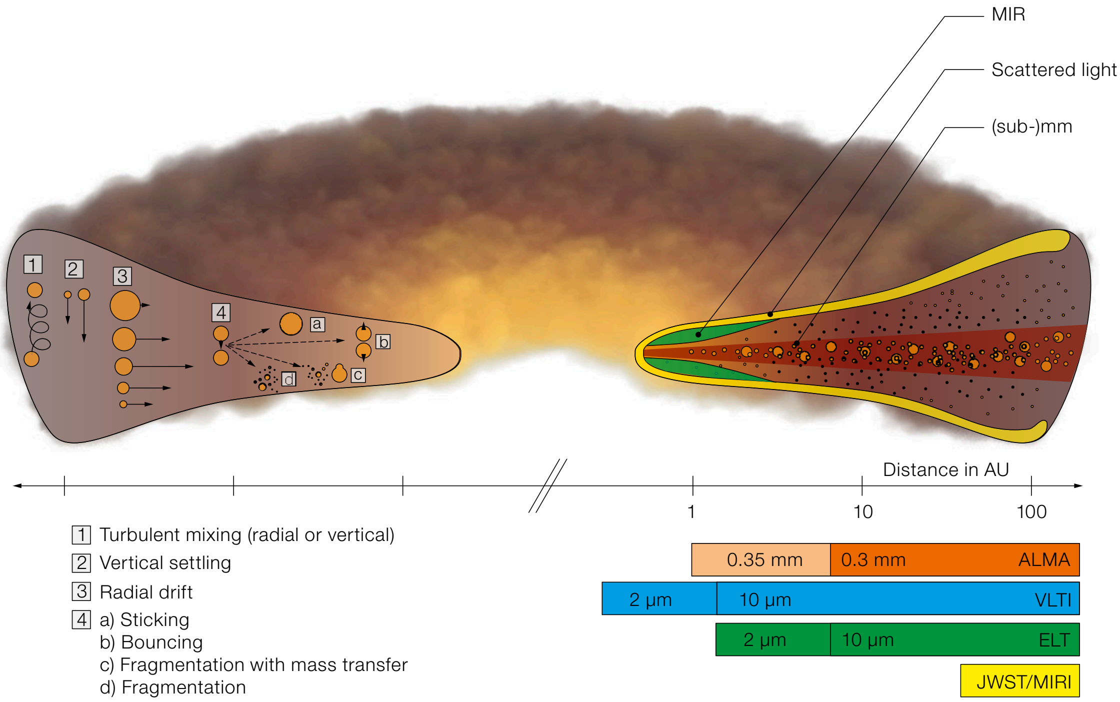

Figure 4. Protoplanetary disc structure, grain evolution processes and observational constraints for protoplanetary discs (the central star is omitted for illustration purposes). The left side shows the dust grain processes, while the right side shows the area of the disc that can be probed using different wavelength ranges and facilities. The VLTI uniquely probes the inner disc in the near infrared (~ 2 µm using PIONIER and GRAVITY), and in the mid-infrared (~ 10 µm using MATISSE). Adapted from Testi et al. (2014), with permission.

expected treasure trove of results. We can already anticipate that both instruments will open up new avenues. The VLTI should aim to be a major contributor to the following astrophysical questions well beyond the immediate horizons:
– Do we understand stars?
– How do planetary systems form?
– How do stars enrich galaxies?
– How do massive stars interact with their environment?
– How do supernova progenitors work?
– What is the prevalence and role of stellar multiplicity?
– Do we understand the immediate surroundings of the Galactic Centre and strong gravity in action?
– Do we understand the interactions between supermassive black holes and their host galaxies?

The VLTI can develop strong synergies with ALMA in all of these areas. In addition, the VLTI could be a significant contributor to the following areas, with the development of new capabilities and exploitation of synergies:
– Improving the cosmological distance scale, by studying Cepheids, the tip of the red giant branch stars, eclipsing binaries, asymptotic giant branch stars, and other distance indicators such as AGN.
– Ground-based astrometric follow up of exoplanet detections post-GAIA.
– Characterisation of host stars in the context of exoplanet and asteroseismology transit missions (for example, via the PLAnetary Transits and Oscillations of stars mission [PLATO]).
– Direct imaging of transient phenomena, such as microlensing events, detected by current and future large-scale photometric surveys (for example, with the Large Synoptic Survey Telescope [LSST]).

Possible future developments

It is of the utmost importance to maintain an active research and development programme in interferometric instrumentation. Taking an example from millimetre interferometry, one can already consider the expansion of the VLTI's capabilities in four areas: imaging, sensitivity, instrumentation, and astrometry. Unlike traditional single-dish instrumentation, which has already developed a number of capabilities, optical interferometry still has a considerable margin for development, as discussed in the recent European Interferometry Initiative report entitled "Future of optical-infrared Interferometry in Europe"[1].

The following capabilities would help to pursue the goals mentioned earlier:

Imaging with a larger number of telescopes

The history of sub-millimetre arrays shows that imaging complex sources can become routine with arrays of seven to eight telescopes. The VLTI is already equipped with eight telescopes (four ATs and four UTs) and six delay lines, even though current instrumentation (PIONIER, GRAVITY, MATISSE) can only combine up to four of these at a time. Additionally, the VLTI delay line tunnels can accommodate two more delay lines. Alternatively, the VLTI platform can host several additional telescopes without major infrastructure modifications.

A first step before expanding VLTI baseline capabilities is to fully exploit the current facility. One of the current limitations for imaging with the ATs is the spatial frequency (uv-plane coverage); the VLTI can only be offered with a maximum baseline length that is 70 % of the longest possible baseline (202 m), and the possible quadruplets of telescopes are limited by their sky coverage. Extending the delay line length could solve both issues. Although the delay line tunnel cannot be extended, delay lines can have their optical path length doubled by folding the optical beam and passing twice through the delay line cart. This would allow the longest AT baseline (202 m) to be offered, and increase the number of possible AT quadruplets with full sky coverage.

Sensitive co-phasing

This improves imaging by allowing the longest baselines (with lowest fringe contrast) to be used, thanks to baseline bootstrapping; it also improves sensitivity and/or spectral resolution, in particular when off-axis fringe tracking, or fringe tracking in a different waveband, is implemented. The VLTI is at the forefront of the development and operation of fringe trackers, thanks to its experience with AMBER+FINITO, the PRIMA Fringe Sensor Units (used with MIDI) and now GRAVITY.

MATISSE requires a fringe tracker to achieve its full scientific potential, for which GRAVITY's fringe tracker will be used initially. However, this might not be optimal and the performance of this combination should be assessed a few years into MATISSE operation. Building a new fringe tracker might be the ultimate solution to improving performance. Improving the facility should also help. The optical transmission not only affects the sensitivity, but fringe trackers are also susceptible to wavefront perturbations that lower their sensitivity. Reaching the diffraction limit and a Strehl ratio of more than 50 % using adaptive optics (AO) will improve fringe tracking sensitivity.

The UTs are equipped with AO dedicated to the VLTI with visible (MACAO) and infrared (CIAO) wavefront sensors. NAOMI, the AO system for the ATs, will be deployed a year from now. Fringe trackers correct for atmospheric perturbations, but the UTs' vibrations still dominate over atmospheric turbulence. Continuous efforts will be required to mitigate and reduce the telescope vibrations in order to maintain and improve the VLTI's sensitivity and dynamic range.

High dynamic range

The current dynamic range of VLTI instruments (about 1:500) limits the ability to address some particularly exciting science cases. The advantage of a dynamic range of 1:1000 to 1:10 000 in the mid-infrared (i.e., *L*- and *M*-bands) was demonstrated at a recent workshop for a new VLTI instrument project (HI-5)[2]. This capability could lead to the direct imaging of planet formation or even young planets.

A wealth of instrumentation developments are currently underway to build high-contrast beam combiners in the *L*- and *M*-bands using single-mode fibres and integrated-optics components, which could lead to simple yet transformative visitor instruments, following in the footsteps of PIONIER. The forthcoming decommissioning of AMBER will open up space for a visitor instrument. The requirements for high dynamic range are intimately linked to the performance of the infrastructure.

Extension to shorter wavelengths (< 1.4 μm)

The main driver for such an extension would be the improvement in spatial resolution, opening up the domain of stellar surface imaging of main sequence stars, which remains mostly unexplored. A visible-light instrument with high spectral resolution would be able to resolve velocity fields, such as rotation or pulsation, at the surface of stars. Other science cases and instrumentation developments are detailed in the recent white book *Science Cases for a Visible Interferometer* (Stee et al., 2017), showing the growing interest from the community. Such developments would require not only new instrumentation, but also significant facility upgrades, since the VLTI only transmits near- and mid-infrared light to the delay lines and laboratory, leaving the shorter wavelengths at the telescopes for guiding purposes.

The roadmap for the VLTI, recommended in October 2017 by ESO's Scientific and Technical Committee[4], can be divided into three epochs:

Epoch 1: until 2020

- Make GRAVITY and MATISSE a success by providing an efficient, optimally scheduled VLTI array. Demonstrate robust fringe tracking and increase sensitivity.
- Expand the VLTI user base by improving accessibility to non-experts, possibly through dedicated VLTI centres that are fostered by ESO and the European Interferometry Initiative[2].
- Organise a conference before 2020 to involve the community in a discussion of possible third-generation instrumentation and upgraded infrastructure for VLTI.

Epoch 2: 2020–2025

- Fully exploit the existing infrastructure by upgrading the existing instrumentation.
- Increase sky coverage and angular resolution by doubling the delay line optical path.
- Host visiting instruments to push interferometric techniques in new directions.

Epoch 3: beyond 2025

- VLTI imaging capability might be expanded by adding more telescopes and building a six- to eight-telescope beam combiner, driven by the ability of the community to propose strong science-driven projects.
- The VLTI could be used as a development platform for next-generation optical interferometers.

This roadmap aims to pave the way for future VLTI developments at ESO, as well as to encourage the community to drive the long-term future of the VLTI.

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Links

[1] Working group on the future of interferometry in Europe: http://www.european-interferometry.eu/working-groups/the-future-of-interferometry-in-europe
[2] Hi-5 Kickoff Meeting website: http://www.biosignatures.ulg.ac.be/hi-5
[3] The European Interferometry Initiative: www.european-interferometry.eu/
[4] ESO Scientific Technical Committee report on VLTI Roadmap STC-599: https://www.eso.org/public/about-eso/committees/stc/stc-90th/public/STC_599_VLTI_Roadmap_90th_STC_mtg_Oct_2017.pdf

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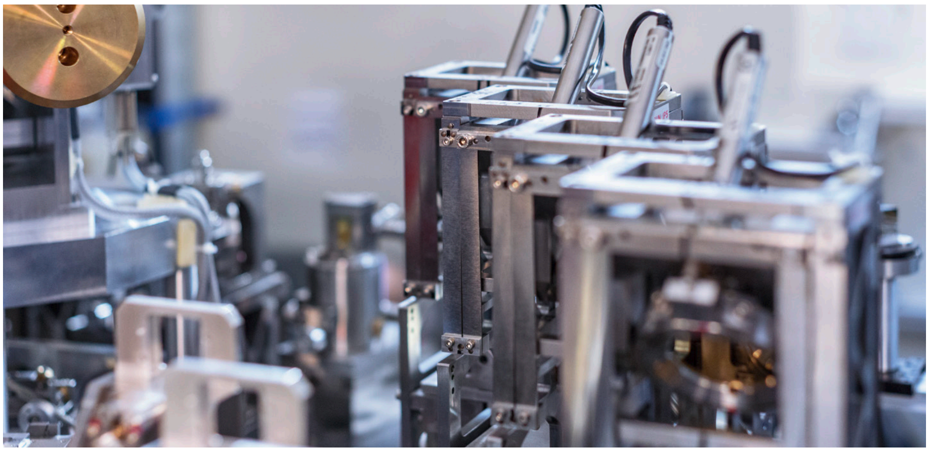

Complex optics on the MATISSE instrument on the VLTI. Many components are repeated four times, one for each beam of light being fed into the instrument.

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The ELT in 2017: The Year of the Primary Mirror

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The Extremely Large Telescope (ELT) is at the core of ESO's vision to deliver the largest optical and infrared telescope in the world. With its unrivalled sensitivity and angular resolution the ELT will transform our view of the Universe: from exoplanets to resolved stellar populations, from galaxy evolution to cosmology and fundamental physics. This article focuses on one of the most challenging aspects of the entire programme, the 39-metre primary mirror (M1). 2017 was a particularly intense year for M1, the main highlight being the approval by ESO's Council to proceed with construction of the entire mirror. In addition, several contracts have been placed to ensure that the giant primary mirror will be operational at first light.

Background: how the ELT works

The optical design of the ELT is based on a novel five-mirror scheme capable of collecting and focusing the light from astronomical sources and feeding state-of-the-art instruments to carry out imaging and spectroscopy. As shown in Figure 1, the light is collected by the giant primary mirror (39.3 metres in diameter), relayed via the secondary and tertiary mirrors, M2 and M3 (both of which have ~ 4-metre diameters), to M4 and M5 (the core of the telescope adaptive optics). The light then reaches the instruments on one of the two Nasmyth platforms.

This design provides an unvignetted field of view (FoV) with a diameter of 10 arcminutes on the sky, or about 80 square arcminutes (i.e., ~ 1/9 of the area of the full moon). Thanks to the combined activation of M4 and M5, it will have the capability to correct for atmospheric turbulence as well as the vibration of the telescope structure induced by its movement and the wind. This is crucial to allow the ELT to reach its diffraction limit, which is ~ 8 milli-arcseconds (mas) in the *J*-band (at λ ~ 1.2 μm) and ~ 14 mas in the *K*-band, thereby providing images 15 times sharper than Hubble Space Telescope.

Translated into astrophysical terms this means opening up new discovery spaces — from exoplanets close to their stars, to black holes, to the building blocks of galaxies — both in the local Universe and billions of light years away. Specific examples include the ability to detect and characterise extra-solar planets in the habitable zone around our closest star Proxima Centauri, or to resolve giant molecular clouds (the building blocks of star formation) down to ~ 50 pc in distant galaxies at redshift z ~ 2, and even smaller structures for sources that are gravitationally lensed by foreground clusters, all with unprecedented sensitivity.

The giant primary mirror

One of the many technological marvels of ESO's ELT is the primary mirror, M1, along with all the necessary infrastructure and control schemes that are needed to make it work. At 39.3 metres in diameter it will be the largest optical/infrared telescope ever built. Of course, this comes with attendant challenges. The mirror is segmented, being made of 798 quasi-hexagonal mirrors, each of which is about 1.45 metres in size (corner-to-corner), is only 50 mm thick and weighs 250 kg. The full M1 has a six-fold symmetry; there are

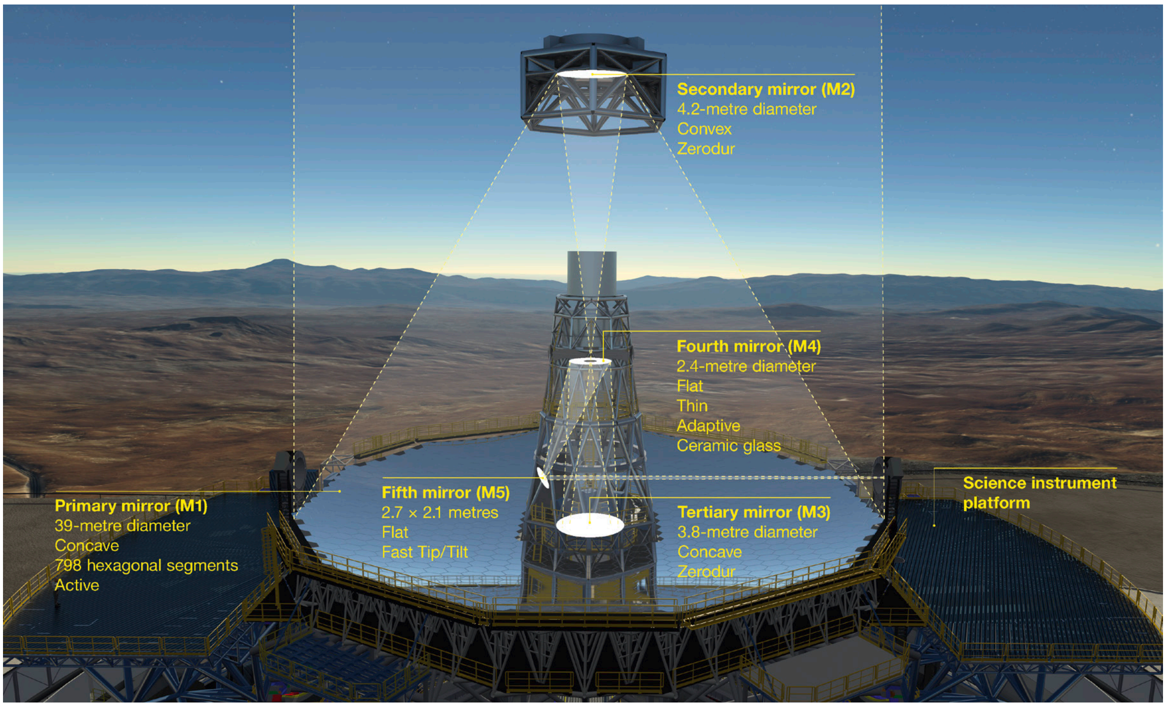

Figure 1. This diagram shows the novel five-mirror optical system of ESO's ELT. Before it can reach the ELT's scientific instruments, light is first reflected from the telescope's giant concave 39-metre segmented primary mirror (M1), after which it bounces off two further four-metre-class mirrors, one convex (M2) and one concave (M3). The final two mirrors (M4 and M5) form a built-in adaptive optics system to allow extremely sharp images to be formed at the final focal plane.

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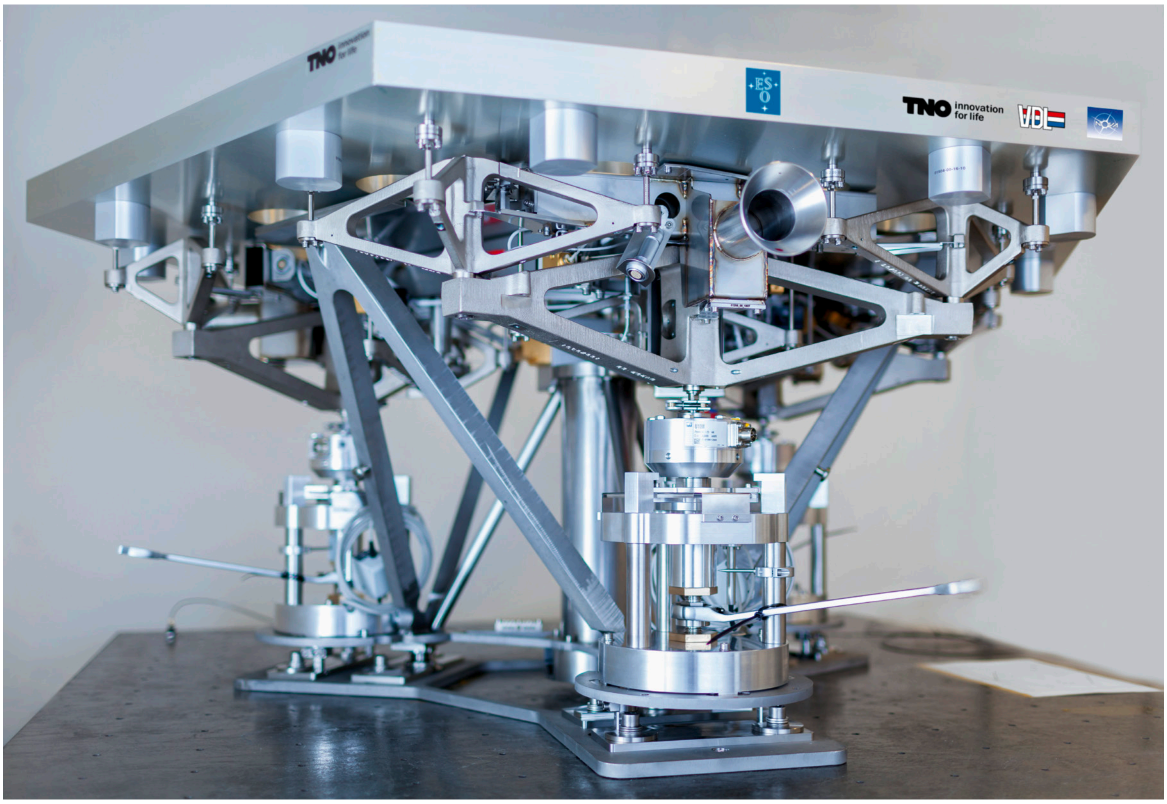


Figure 2. One segment support structure of the giant primary mirror of the ELT undergoing testing.

six identical sectors of 133 segments each. In each sector all 133 segments are different from each other in shape and optical prescription; in other words there are 133 different segment types. In order to facilitate recoating there will be a seventh sector with 133 segments, i.e., one for each segment type. This adds up to a grand total of 931 segments.

M1 is evidently a very complex system. Therefore, to achieve the required scientific performance, it needs to be maintained in position and be phased to an accuracy of tens of nanometres — 10 000 times thinner than a human hair — across its entire 39-metre diameter! This is extremely challenging, as the full structure will be moving constantly during an observation, and will be affected by wind and thermal changes.

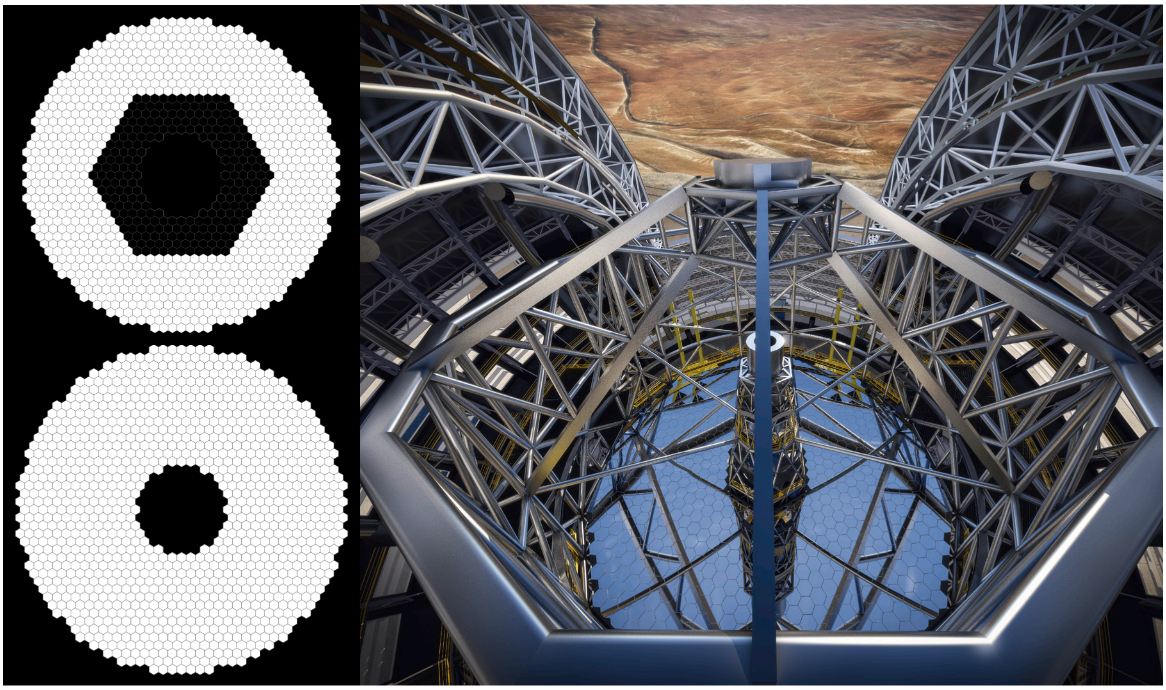
There are various ways in which M1 can be actively controlled. Each segment, made of the low-expansion ceramic material Zerodur© (from SCHOTT), is supported on a 27-point whiffletree, which is a mechanism to evenly distribute the support across the back of the segment using 27 points of contact across its surface. The load on the whiffletree can be adjusted via warping harnesses so as to slightly change the shape of the mirror to compensate for optical aberrations induced by gravity and thermal effects (see Figure 2). Moreover, each segment assembly can be moved in height and tip/tilt relative to the structure by using three positioning actuators (PACTs). These three actuators can move independently with an accuracy of 2 nm with a maximum excursion (or stroke) of 10 mm to adjust its position and maintain the perfect co-alignment of all the segments and effectively create a giant monolithic mirror. To achieve this, each side of each hexagonal segment has two “edge sensors” that constantly measure piston, gap and shear with respect to the adjacent segment to nanometre accuracy and provide the necessary information to the control system to activate the PACTs, allowing the segments to work together to form a perfect imaging system.

All in all, the M1 is a colossal system, featuring a staggering 798 segments, almost 2500 PACTs and about 9000 edge sensors (4500 pairs), not including the seventh sector and the spares.

ESO Council approval of the full M1

When the construction of the ELT was approved by Council in December 2014, it was split into two phases. Phase 1 was for the 39-metre ELT with the Multi-AO Imaging CAmera for Deep Observations (MICADO), the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI) and the Mid-infrared ELT Imager and Spectrograph (METIS) instruments and the Multi-conjugate Adaptive Optics RelaY (MAORY) adaptive optics module. The Phase 1 ELT was still capable of achieving breakthrough discoveries, although it excluded a number of critical components, notably the five inner rings (Figure 3), the seventh sector of segments for M1, and one of the facilities needed to maintain the quality of the M1 coating. The intention was to include these items in a second phase of construction at a later date.

ESO’s management and governing bodies always recognised the critical importance of these Phase 2 items. Hence, at its December 2017 meeting, following positive recommendations from



ESO/L. Calçada/ACe Consortium

Figure 3. Left: Schematic graph comparing the Phase 1 M1 (top) without the 5 inner rings, i.e., only 588 mirrors and a large central obscuration, and the full M1 as now approved by ESO Council (bottom) with 798 segments, including the Phase 2 segments. Right: A view of M1, once it is mounted on the main structure.

the external ELT Management Advisory Committee (EMAC) and from ESO's statutory advisory bodies, the Scientific and Technical Committee (STC) and Finance Committee (FC), the ESO Council gave its authorisation to exercise contractual options to procure the previous unfunded Phase 2 items related to M1 (i.e., the five inner rings, the seventh sector and the second M1 maintenance unit). This decision enables the highest possible science return for users and for instrumentation, lowers the risk to the programme and lowers the final cost of the full ELT. Indeed, if M1 segment production were to be stopped after Phase 1 between 2019 and 2020, the costs involved in restarting the production of the blanks, segment polishing and the mirror supports at a later date would almost certainly be prohibitive, especially if the same stringent tolerances had to be maintained after (potentially) reopening and refurbishing the production facilities.

The full M1, including the inner five rings, has clear advantages regarding scientific return. It expands the collecting area of the primary mirror by 36 % compared to the Phase I configuration, which increases its sensitivity (i.e., its capability to efficiently collect light from fainter and/or more distant sources). It reduces the linear size of the central hole by nearly a factor of two (see Figure 3), which improves the ability to control the shape of the mirror surface. Filling the gap and reducing the linear obscuration is also very important for the ELT's ultimate performance as it is easier to concentrate light on science detectors with a smaller central obscuration; the peak of the point spread function (PSF) is a factor of two higher. This means that the energy is more focused, further increasing sensitivity and improving the adaptive optics performance and sky coverage. A smaller central obscuration is particularly important for the study of exoplanets using the technique of high-contrast imaging: the better the PSF the easier it is to suppress the light from the much brighter central star and to detect planets that are close to the star, thereby making the goal of directly observing Earth analogues attainable.

Making the M1 mirror

Now that the ESO Council has approved the construction of the full M1, procurement and production of the various components of M1 are going ahead. Indeed, 2017 is known as "the year of M1" within the ELT project, reflecting the many steps that were taken towards the fabrication of the various M1 components, including segment blanks, segment polishing, segment supports, PACTs, edge sensors, and the M1 Control System.

All major contracts related to these components of M1 have been approved, signed and initiated, except for the series production of M1 segment supports, the contract for which is expected to be awarded in early 2018. The timely initiation of all of these contracts is particularly important for two reasons: first, M1 fabrication lies on the so-called critical path for the ELT, meaning that any delay would have a direct impact on the date of first light; second, these contracts are interdependent. For example, the blank is required to start the polishing, and the segment support is required at the end of the polishing process for final testing and ion-beam figuring.

As 2017 was such a successful year for procurement, we can provide some details about the major contracts involved. In a ceremony held in January 2017, a contract was signed for the production of the edge sensors with FAMES, a consortium composed of Fogale (France) and Micro-Epsilon (Germany), together with three other ELT procurements (the M2 and M3 Cells with SENER and the blanks for M2 and M3 with SCHOTT). The contract with FAMES covers the design and fabrication of a total of approximately 9000 edge

SCHOTT/ESO

Figure 4. This image shows the first cast from which six blanks will be obtained by SCHOTT (Germany) at their facility in Mainz. This first cast is a thick cylinder that will be cut into six slices, each of which will become a segment blank.

sensors (~ 4500 pairs) for the 798 hexagonal segments of M1. These sensors are the most accurate to ever be used in a telescope and can measure the relative positions of the segments to an accuracy of a few nanometres. The challenge in this case is two-fold — the sensors must reliably provide the required precision, and production must proceed at an appropriate pace to deliver thousands of sensors by the specified deadline.

At a joint signature ceremony at the end of May 2017, two important contracts were signed to produce the 798 segments for the M1. The first one was signed with SCHOTT (Germany) for the production of the blanks. The second one was signed with Safran Reosc (France) for the polishing of the blanks and their integration with the segment supports. These are two of the most prominent companies involved in European astronomy, and the ceremony was a great occasion for their teams and the ESO management involved in the project to meet and shake hands, effectively forming a partnership and becoming part of a larger "family" working together to build ESO's ELT.

Production has already started, and in January 2018, the first six segment blanks were successfully cast by the German company SCHOTT at their facility in Mainz (Figure 4). After casting, the mirror segment blanks will go through a process of slow cooling and heat treatment. The blanks will then be delivered by SCHOTT to Reosc to figure and polish the segments, cut them into hexagonal shapes, integrate them into their support systems, and perform optical tests before delivery to Chile. During the polishing process, each segment will be polished until it has no surface irregularity greater than about 8 nm. To meet the challenge of delivering such a large number of polished segments within seven years, Safran Reosc will build up to a peak production rate of one mirror a day. To meet this demand, Safran Reosc has already begun the necessary refurbishment of a facility at their Poitiers plant. The contract for the segment polishing is the second-largest contract for the construction of the ELT, after the one for the dome and telescope structure, which was awarded to the Ace Consortium in May 2016. It is also the third-largest contract ESO has ever signed.

In June 2017, ESO also signed a contract with the company Physik Instrumente GmbH & Co. KG (Germany) to manufacture the PACTs, which will continuously adjust the positions of the 798 hexagonal segments of M1 on the telescope structure. Apart from the external contracts, M1 also requires a significant amount of work internally at ESO; in October 2017, the final design review of the M1 Local Control System (LCS) was completed and there is now a focus on building a critical test bench to develop and validate the telescope wavefront control algorithms.

This is only a fraction of the impressive amount of work going on, both at ESO and at the various industrial partners, towards the efficient, accurate and timely manufacturing of all the various components that will make up the ELT.

The life of the M1 mirror

It should be noted that the manufacturing, assembly and installation of M1 only represent its first steps, as M1 will lead a life that requires constant reconfiguration. Indeed, to maintain the best reflectivity and sensitivity of the telescope, each mirror will need to be recoated every 18 months, like the mirrors of the VLT. Given the number of segments, this means removing, recoating and reinstalling two segments on the telescope every day for the entire lifetime of the telescope. This represents a significant logistical effort, in order to keep up an efficient stripping, washing and coating process, as well as a well-defined maintenance plan for the thousands of ELT components. For this reason, the seventh sector of segments and the second maintenance unit (including the washing, stripping and coating plants) are particularly crucial for managing the efficient recoating of segments without regularly creating temporary holes in M1. This ensures optimal mirror control and image quality at the lowest operational costs, especially for the most demanding extreme adaptive optics applications.

The M1 mirror is certainly one of the most challenging sub-systems of the entire ELT Programme. It comprises thousands of highly sophisticated components that require extreme accuracy, not only during their manufacture, but also during installation and observations. This is certainly a challenge and the ELT Team is closely following the development of all the M1 components to ensure the ELT's first light in 2024.

Astronomical Science

Image of filamentary structure in a giant molecular cloud in the Orion Nebula. Millimetre (red) and infrared (blue) observations taken with ALMA, IRAM and HAWK-I reveal high-density material down to 0.009 parsec (2000 au) scales. The image is oriented so that north-south runs from the top right to the lower left.

ESO/H. Drass/ALMA (ESO/NAOJ/NRAO)/A. Hacar

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Exploring the Sun with ALMA

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The Atacama Large Millimeter/submillimeter Array (ALMA) Observatory opens a new window onto the Universe. The ability to perform continuum imaging and spectroscopy of astrophysical phenomena at millimetre and submillimetre wavelengths with unprecedented sensitivity opens up new avenues for the study of cosmology and the evolution of galaxies, the formation of stars and planets, and astrochemistry. ALMA also allows fundamentally new observations to be made of objects much closer to home, including the Sun. The Sun has long served as a touchstone for our understanding of astrophysical processes, from the nature of stellar interiors, to magnetic dynamos, non-radiative heating, stellar mass loss, and energetic phenomena such as solar flares. ALMA offers new insights into all of these processes.

ALMA solar science

Radiation from the Sun at millimetre and submillimetre wavelengths largely originates from the chromosphere, the relatively thin interface between the radiation-dominated photosphere and the magnetically dominated corona. The chromosphere is highly dynamic in nature as magnetohydrodynamic (MHD) waves propagate up from the photosphere below and form shocks that dissipate their energy (for example, Wedemeyer, 2016).

The chromosphere remains an outstanding problem in solar physics and, by extension, stellar physics. The central question is: why does the Sun's atmosphere increase in temperature above the visible photosphere as one proceeds up through the chromosphere and into the corona? What are the heating mechanisms? How is energy transported? What is the role of the magnetic field? ALMA is needed to help establish the thermodynamic structure of the chromosphere and to gain an understanding of how mechanical and radiative energy are transferred through that atmospheric layer.

Much of what is currently known about the chromosphere has relied on spectroscopic observations at optical and ultraviolet wavelengths using both ground- and space-based instrumentation. While a lot of progress has been made, the interpretation of such observations is complex because optical and ultraviolet lines in the chromosphere form under conditions of non-local thermodynamic equilibrium. In contrast, emission from the Sun's chromosphere at millimetre and submillimetre wavelengths is more straightforward to interpret as the emission forms under conditions of local thermodynamic equilibrium and the source function is Planckian. Moreover, the Rayleigh-Jeans approximation is valid ($hn/kT \ll 1$) and so the observed intensity at a given frequency is linearly proportional to the temperature of the (optically thick) emitting material. By tuning across the full suite of ALMA's frequency bands it is possible to probe the entire depth of the chromosphere.

Wedemeyer et al. (2016) comprehensively discuss the potential of ALMA in this context. In brief, observations of thermal emission from material at chromospheric temperatures will be a mainstay of ALMA's solar physics programme. Multiband, high-resolution, time-resolved observations of the chromosphere at millimetre and submillimetre wavelengths with ALMA will play a key role in constraining models of chromospheric and coronal heating.

In addition, ALMA will be important for addressing puzzles associated with solar filaments and prominences that form along magnetic neutral lines. Although they are at chromospheric temperatures, they occur at coronal heights and are therefore immersed in much hotter plasma. Quiescent prominences can remain stable for days or even weeks but may then become unstable and erupt. ALMA offers new insights into the thermal structure and dynamics of prominences, their formation, and their eventual loss of equilibrium.

ALMA observations of non-thermal emission will also be of crucial importance. Although observations of small flares or small eruptive events may be observed using the existing modes described below, observations of solar flares are not yet feasible with ALMA in general. Unlike quiescent solar emission, solar flares produce intense non-thermal radiation as a result of energetic electrons interacting with the local magnetic field. ALMA will be sensitive to emission from the most energetic of these electrons. An important discovery by Kaufmann et al. (2004) is that some flares produce a spectral component at millimetre/submillimetre wavelengths with an inverted spectrum — the so-called "sub-terahertz" component, which is distinct from the non-thermal gyrosynchrotron component. Krucker et al. (2013) discuss it at length, yet the origin of the sub-terahertz flare component remains unknown. ALMA will play a central role in understanding its origin.

Each of these broad science themes additionally informs the burgeoning field of "Space Weather", which is aimed at understanding the drivers of disturbances in the solar corona and wind and their effects on Earth and the near-Earth environment.

Enabling solar observing with ALMA

Building on preliminary work performed in East Asia, Europe, and by the Joint ALMA Observatory, the Solar Development Team was formed in late 2013, supported by the National Science Foundation, ESO and East Asia. Its aims were to enable solar observations with ALMA. The work is supported by an extensive science simulations effort — the Solar Simulations for the Atacama Large Millimetre Observatory Network (Wedemeyer et al., 2015). For example, Heinzel et al. (2015) simulated high-resolution observations of fine structures in solar prominences at millimetre wavelengths. Extensive testing and validation were carried out in 2014 and 2015, leading to the acceptance of solar observing with ALMA in Cycle 4 (see below).

Support for solar science was part of the ALMA science programme from its inception, yet considerable work was needed in practice to implement solar observing modes — work that is still ongoing. Provisions were made to ensure that ALMA antennas could safely point at the Sun without damaging the extremely precise telescope hardware; in particular, the surface panels were chemically roughened in order to scatter optical and infrared radiation and reduce the radiative heating of the sub-reflector and other elements to safe levels. However, there are additional factors to consider when observing the Sun. While ALMA's sensitive receivers are not damaged by pointing at the Sun, they saturate when such an intense signal is introduced into the system, resulting in a strongly non-linear performance.

There are two approaches to mitigating the problem: attenuate the signal introduced into the receiver, or increase the "headroom" of the receiver to ensure that its response remains linear by reducing the receiver gain. Both approaches are possible with ALMA. The first approach was implemented through the use of a solar filter on the ALMA Calibration Device. The solar filter attenuates the incident signal by a frequency-dependent amount that allows solar observations in a given frequency band. However, solar filters have a number of undesirable properties for mapping the quiet (i.e., non-flaring) Sun: they greatly reduce the sensitivity with which calibrator sources can be observed; they cause frequency-dependent complex gain changes; and they introduce significant wavefront errors into the illumination pattern of the antenna, which result in distortions to the antenna beam shape and increased side lobes. Therefore, while solar filters will be needed for observations of stronger solar flares, the second approach was developed for quiet Sun programmes.

Yagoubov (2013) pointed out that the ALMA superconductor-insulator-superconductor (SIS) mixers could be de-tuned or de-biased to reduce the mixer gain and effectively increase the level at which receivers saturate, thereby allowing solar observing without the use of the solar filters. This idea is illustrated in Figure 1, which shows the SIS current gain (left axis) and conversion gain (right axis) plotted against the voltage bias for ALMA Band 3. The normal voltage bias tuning is on the first photon step where the gain conversion is a maximum. However, the mixer still operates at other voltage bias settings. These produce lower conversion gain but, since the dynamic range scales roughly inversely with gain, these settings can handle larger signal levels before saturating. This operational mode is referred to as the mixer de-biased (MD) mode. Observing both the source and calibrators in a specific MD mode obviates the need to explicitly measure the change in system gain introduced by the mode.

Another consideration, however — regardless of whether the solar filter or the MD mode is used — is that the input power changes significantly as the antennas move from the (solar) source to a calibrator and back. Signal levels must remain within nominal limits along the path to the analogue-to-digital converters and the correlator. Stepped attenuators

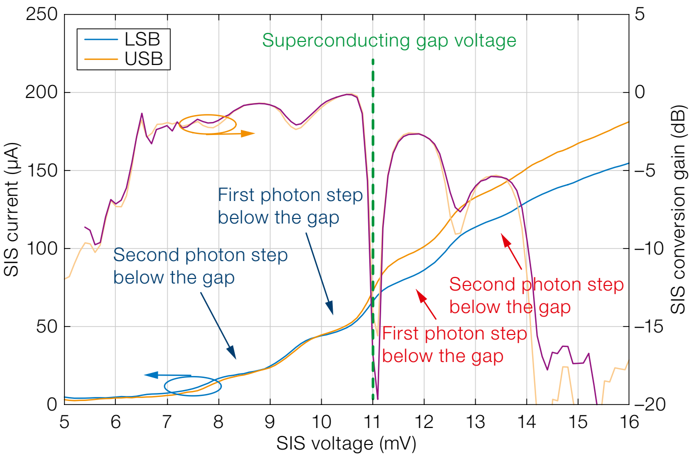

Figure 1. Plot of SIS current and conversion gain as a function of voltage setting for ALMA Band 3 at a local oscillator frequency of 100 GHz. The arrowed ellipses indicate the relevant ordinate: left for the SIS current and right for the conversion gain. See Shimojo et al. (2017a) for additional details.

are used for this purpose. A concern was whether the variable attenuators themselves would introduce unacceptable (differential) phase variation between the source and calibrator settings, thereby corrupting phase calibration referenced against suitable sidereal calibrators. A second concern was whether there are differences between the spectral window bandpass response between source and calibrator scans as a result of attenuator settings. It is a testament to the system design that neither concern proved to be a significant issue. Extensive testing in 2014 showed that the different attenuator settings used to observe calibrator sources and the Sun do not introduce significant phase errors or distort the frequency bandpass. MD observing modes were therefore adopted as the basis for observations of the quiet Sun.

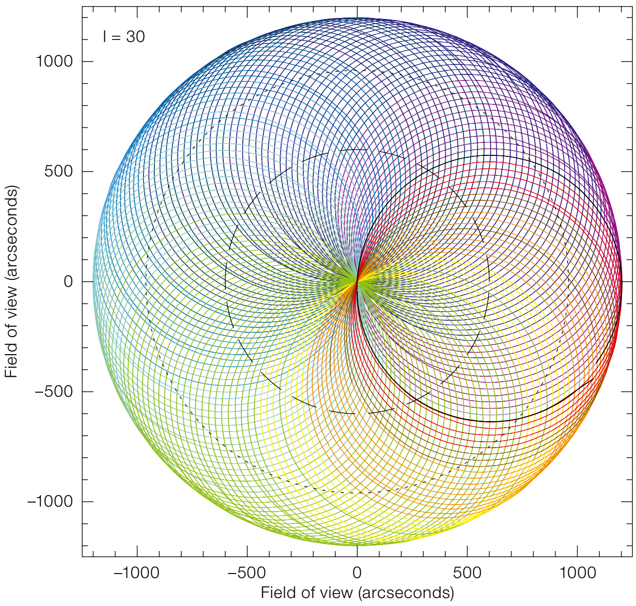

Figure 2. Example of the double-circle pattern used to perform single-dish fast-scan total power maps of the solar disc, with a map spacing of 30 arcseconds. The dotted line indicates the solar limb (radius 960 arcseconds). The rainbow colour variation indicates the progress of the pointing pattern with time and the dashed line indicates the track of the centroids of the individual minor circles in the pattern. See White et al. (2017) for additional details.

Two additional challenges are posed by solar observations. First, the complex brightness distribution of the Sun contributes significant power on angular scales ranging from sub-arcsecond scales to the diameter of the solar disc, the details of which vary on short timescales (tens of seconds). Good instantaneous sampling of the aperture plane is needed to recover measurements over the full range of angular scales. The 7-metre antennas in the fixed Atacama Compact Array were therefore included as well as those in the 12-metre array so as to sample a broader range of angular scales. All antennas were processed through the baseline correlator. In order to recover the Sun's brightness distribution on the largest angular scales, all interferometric observations were supplemented by full-disc fast-scan total power maps (Phillips et al., 2015) in the relevant frequency bands (Figures 2 and 3). These can be combined with the interferometric data via "feathering" to produce photometrically accurate maps of the Sun's brightness distribution.

Second, water vapour radiometers (WVRs) are used on each ALMA antenna to measure variations in the electrical path length introduced by the overlying atmosphere. These measurements are particularly important on long interferometric baselines for correcting differential phase variations. Unfortunately, the WVRs saturate when ALMA's antennas are pointed at the Sun and WVR measurements are therefore unavailable for solar observations. As a consequence, observations of the Sun with long-baseline antenna configurations cannot currently be supported.

The extensive solar development efforts required to bring solar observing modes to the solar community are documented in two papers. Shimojo et al. (2017a) discuss the steps necessary to implement

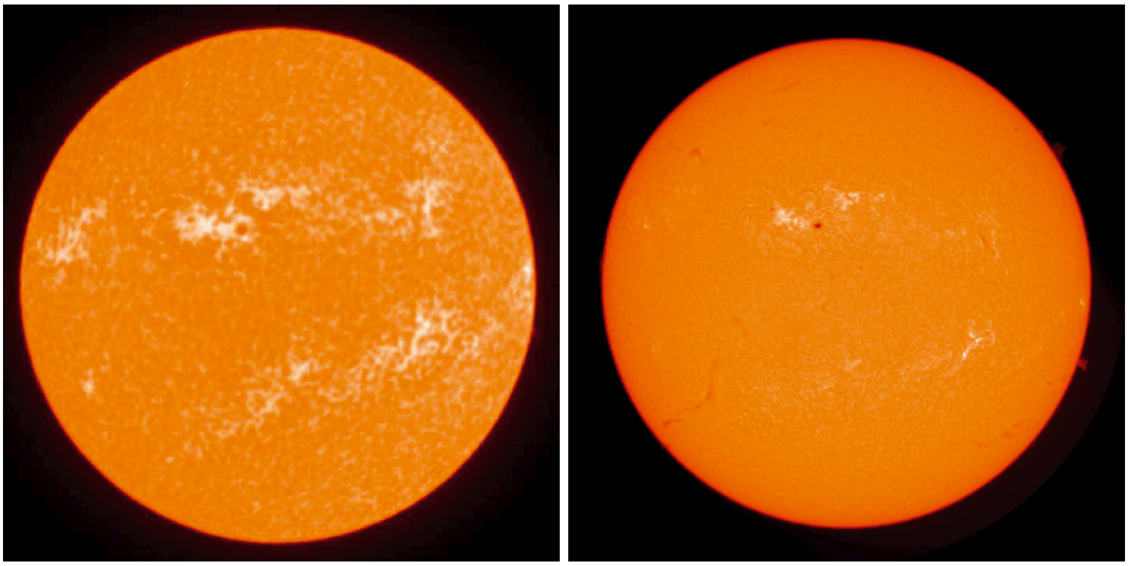
Figure 3. Left: Example of a full-disc fast-scan total power map in Band 9 (0.45 mm) on 18 December 2015 using a scan pattern similar to that shown in Figure 1. Right: The corresponding image in Hα.

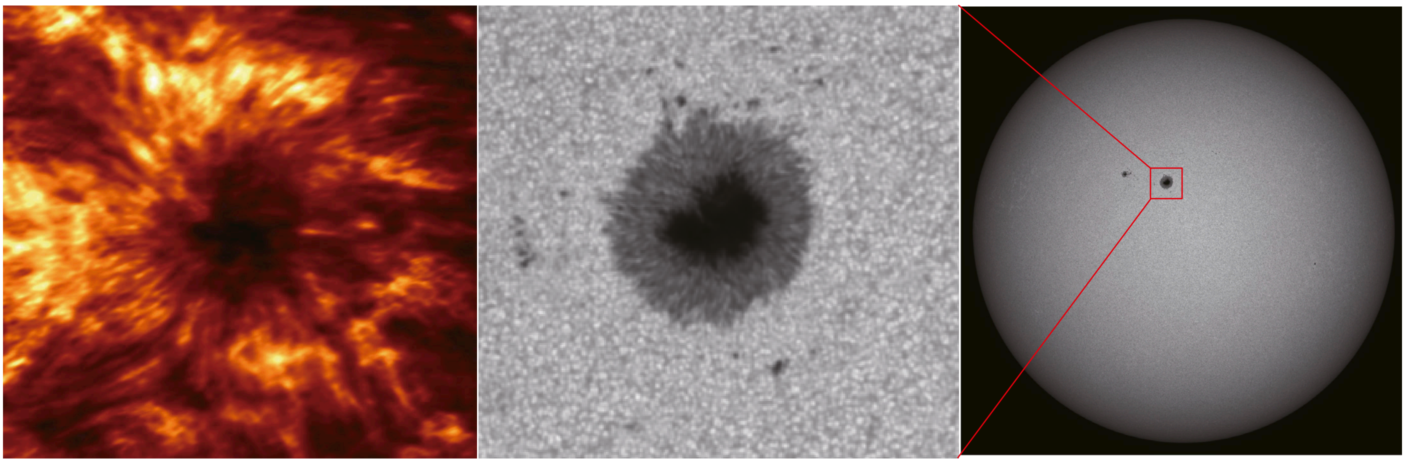

Figure 4. Right: A white-light continuum image of the Sun obtained by the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory showing a sunspot imaged by ALMA. Centre: A detail of the same. Left: Map of the sunspot in Band 6 (1.25 mm). The map was formed by a mosaic of 149 individual antenna pointings. The data were acquired as part of science verification on 18 December 2015. See Shimojo et al. (2017) for additional details.

interferometric imaging of the Sun, and White et al. (2017) describe fast-scan total power mapping of the Sun. Examples of maps obtained by ALMA during science verification are shown in Figures 3 and 4.

ALMA Cycle 4

Solar observing was first made available to the community in Cycle 4 with the call for proposals in March 2016. Cycle 4 solar programmes were restricted to continuum observations in two frequency bands, Band 3 (3 mm) and Band 6 (1.25 mm) using MD mode observing. Since WVR measurements are not possible, solar observing programmes were further restricted to the use of the three most compact 12-metre antenna configurations (C40-1, C40-2, and C40-3). Using C40-3, the maximum possible angular resolutions for Bands 3 and 6 were approximately 1.5 arcseconds and 0.63 arcseconds, respectively.

Nearly 50 solar proposals were received in Cycle 4 and roughly a third of these were approved and allocated observing time at priority A or B. The solar physics community is inherently multi-wavelength in practice. A wide variety of ground- and space-based assets are available that add tremendous scientific value to ALMA observations. For Cycle 4, these include the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al., 2014), which is led by NASA and operates at ultraviolet wavelengths, and the Hinode mission, which is led by the Japan Aerospace Exploration Agency (JAXA) in cooperation with NASA, the UK Science and Technology Facilities Council (STFC), ESO, and the Norwegian Space Centre (Kosugi et al., 2007), and which operates at optical, extreme ultraviolet (EUV), and soft X-ray wavelengths. Numerous ground-based optical telescopes also participated.

Emission from the Sun can change dramatically on short timescales. Even so-called “quiet” Sun emission from non-flaring active regions may evolve significantly over the course of a day. Meeting the science goals of a particular programme may therefore pose operational and scheduling challenges. The need to respond quickly to changing targeting requests is of paramount importance. In order to image a specific target on the Sun, ALMA must correctly track the Sun’s physical ephemeris, offsets relative to the physical ephemeris, and its rotation. ALMA can accommodate observations of ephemeris objects such as the Sun through user-provided files that specify the exact target coordinates as a function of time. A convenient tool, the ALMA solar ephemeris generator — based on the Jet Propulsion Laboratory (JPL) HORIZONS web interface[1,2] — was developed by Ivica Skokić to generate files like these quickly. A solar observer can now specify the target offset relative to the centre of the Sun, and use a model to correct for the Sun’s differential rotation.

An observing strategy that mitigates, in part, some of the complexity associated with scheduling solar programmes is to execute them during an “observing campaign”. That is, in coordination with relevant missions and telescopes, a fixed window of time is designated in one or more antenna configurations during which the bulk of the ALMA solar observing is discharged. This worked well for Cycle 4 observing programmes from an operational standpoint, although the communication strategy between the ALMA Principal Investigator, the ALMA duty astronomer and ALMA operations needs further refinement.

Early science

ALMA science verification data were released to the community in January 2017[3,4]. These data[4] validated solar observing modes released to the community for Cycle 4 observing and have served as the basis for a number of recent scientific papers. Several studies made full use of the interferometric and fast-scan total power data and others made use of the superb fast-scan total power maps of the full disc of the Sun alone:

– Shimojo et al. (2017b) studied the eruption of a plasmoid in a solar active region jointly at 3 mm, in the EUV (Solar Dynamics Observatory) and in soft X-rays (Hinode), demonstrating the utility of both the time-resolved, snapshot imaging capabilities of ALMA and the use of multi-wavelength observations to constrain the properties of the plasmoid.

- Bastian et al. (2017) compared ALMA 1.25-mm observations of an active region with the corresponding observations of the Mg II ultraviolet emission made by IRIS. The ALMA data comprised a 149-point mosaic of a solar active region that was feathered with the corresponding fast-scan total power map. Although believed to form at similar heights in the chromosphere, there are distinct differences between the millimetre brightness temperature and the ultraviolet radiation temperature, which are attributed to regional dependencies of the formation height and/or an increased degree of coupling between the ultraviolet source function and the local gas temperature in hotter and denser areas of the active region.

- Iwai et al. (2017) discovered a significant 3-mm brightness enhancement in the centre of a sunspot umbra that is coincident with enhancements in the 1330 Å and 1400 Å ultraviolet continuum images observed by IRIS. The enhancement may be intrinsic to sunspot umbrae at chromospheric heights, or alternatively could be the millimetre counterpart to a polar plume.

- Loukitcheva et al. (2017a) made detailed comparisons of ALMA observations of a sunspot at 1.25 and 3 mm with models of sunspot umbrae and penumbrae, finding that none of the extant models gives a satisfactory fit to the dual-band high-resolution ALMA observations. Observations between 1.25 and 3 mm (Bands 4 and 5) are needed, as well as additional multiband observations of many more sunspots.

- Allisandrakis et al. (2017) exploited fast-scan total power maps at both 1.25 and 3 mm to assess the brightness variation of the quiet Sun from the centre to the limb, inverting the transfer equation to infer the dependence of plasma temperature on optical depth.

- Brajša et al. (2018) also used fast-scan total power maps to characterise the Sun's millimetre radiation in comparison with the chromospheric and coronal emission seen at optical and EUV wavelengths, finding a high degree of correlation, even including millimetre counterparts to coronal X-ray bright points.

These early results already anticipate the richness and diversity of the solar observations to come under regular observing. With the support of additional frequency bands and new capabilities, the breadth of solar science that can be addressed by ALMA will be fully realised. We conclude with a brief discussion of future capabilities for solar observing.

Future capabilities

To date, ALMA has barely scratched the surface of the scientific potential of millimetre and submillimetre observations of the Sun. In addition to analysing and publishing the wealth of results from Cycle 4 observations in Bands 3 and 6, much work remains to enable observations in additional frequency bands and to deploy new observing modes. These, in turn, will allow the full power of ALMA to be brought to bear on the fundamental science questions outlined above.

Additional frequency bands

The frequency range sampled by ALMA offers a powerful probe of the solar chromosphere. At present, observations in Band 3 and Band 6 are supported. The intention of the Solar Development Team is to provide support for observations in Band 7 (0.85 mm) and Band 9 (0.45 mm) in Cycle 7 to allow deeper layers of the chromosphere to be observed. Evaluation of Bands 7 and 9 for solar observing is currently under way. In future years, observations in frequency bands filling the gaps between Bands 3, 6, 7, and 9 will be enabled.

Polarimetry

A key capability of ALMA for all scientific communities is to fully support the quantitative characterisation of the polarisation properties of the observed millimetre/submillimetre radiation, usually in the form of the Stokes polarisation parameters. Of fundamental importance to understanding a range of physical processes is the measurement of chromospheric magnetic fields. Ultimately, measurements of Stokes V (circular polarisation) to a precision of 0.1 % are needed to fully exploit polarimetric observations of the Sun. Details of how solar polarimetric observations will be exploited and the requirements for ALMA are discussed by Loukitcheva et al. (2017b).

Imaging spectroscopy

Support for spectral-line-mode observing is required to detect and exploit observations of radio recombination lines (RRLs) and, possibly, other atomic and molecular transitions in the solar atmosphere. Clark et al. (2000a, b) reported line widths of order 500 MHz for the hydrogen RRLs H21α and H19α, suggesting that relatively low-resolution “time division mode” observations with ALMA may be sufficient for early exploitation of RRLs.

Solar flares

The strategy employed for observing the quiet Sun in Bands 3 and 6 using the MD receiver modes will not be feasible for solar flares, which can produce intense radiation that far exceeds the ubiquitous thermal background of the solar chromosphere. For solar flare observations solar filters must be used. The East Asia team has previously demonstrated the use of solar filters for flare observations but detailed calibration procedures have yet to be fully defined.

Science subarrays

The spectrum of continuum radiation from the Sun is a key observable. Given the dynamic nature of solar emissions at millimetre and submillimetre wavelengths, observations are needed in as many frequency bands as possible on a timescale commensurate with the phenomenon of interest. In practice, this is a challenge. It may be possible to timeshare between two or more frequency bands on timescales of tens of seconds for some programmes, but others (for example, observations of solar flares) will require strictly simultaneous observations in two or more frequency bands. This will require dividing the array into two or more subarrays that are each capable of observing the Sun independently.

Fast regional mapping

Solar-mode observing currently includes support of full disc total power mapping as an adjunct to the interferometric observations. The total power maps have scientific value in their own right and, for certain applications, may be preferable to interferometic observations. The ALMA Solar Development Team has demonstrated that fast-scan mapping could be performed on sub-regions of the Sun at a relatively high cadence (tens of seconds). Continuous fast-scan mapping of regions on scales of just a few arcminutes using two or more total power antennas to provide multi-band imaging would be a valuable mode to observe certain aspects of solar flares and eruptive phenomena.

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Links

[1] The ALMA solar ephemeris generator: http://celestialscenes.com/alma/coords/CoordTool.html
[2] JPL Horizons web interface: https://ssd.jpl.nasa.gov/horizons.cgi
[3] ALMA solar observations: http://www.almaobservatory.org/en/announcement/alma-starts-observing-the-sun/
[4] ALMA science verification data: https://almascience.nrao.edu/alma-data/science-verification

D. Kordan/ESO

ALMA in 2017, just after a particularly harsh winter.

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The ESO Diffuse Interstellar Band Large Exploration Survey (EDIBLES) is a Large Programme that is collecting high-signal-to-noise (S/N) spectra with UVES of a large sample of O and B-type stars covering a large spectral range. The goal of the programme is to extract a unique sample of high-quality interstellar spectra from these data, representing different physical and chemical environments, and to characterise these environments in great detail. An important component of interstellar spectra is the diffuse interstellar bands (DIBs), a set of hundreds of unidentified interstellar absorption lines. With the detailed line-of-sight information and the high-quality spectra, EDIBLES will derive strong constraints on the potential DIB carrier molecules. EDIBLES will thus guide the laboratory experiments necessary to identify these interstellar "mystery molecules", and turn DIBs into powerful diagnostics of their environments in our Milky Way Galaxy and beyond. We present some preliminary results showing the unique capabilities of the EDIBLES programme.

The diffuse interstellar bands

One of the longest-standing problems in modern astronomical spectroscopy is associated with the identification of the chemical species that produce the diffuse interstellar bands (DIBs; see Cami & Cox, 2012 for a recent review) — a problem that first surfaced almost a century ago. The DIBs are a collection of over 400 absorption features that appear in the spectra of reddened stars. Their interstellar nature is clear, but their origin is unknown (although a few DIBs in the near-infrared part of the spectrum are attributed to C_{60}^{+}; see below). Given their strength and their widespread occurrence in harsh interstellar environments, the DIB carriers are most likely abundant, stable, carbonaceous species such as carbon chains, polycyclic aromatic hydrocarbons (PAHs), fullerenes or closely related species. Despite their unknown identity, the DIBs are being used increasingly often as tools, for example to map the interstellar medium in 3D (Bailey et al., 2016). The eventual identification of DIB carrier(s) will make DIBs very powerful diagnostics in the interstellar medium.

The definite identification of DIB carriers must come from an accurate match between the observed spectroscopic features in a low-temperature gas-phase laboratory experiment and the DIBs seen in astronomical observations. Indeed, laboratory data not only provide accurate rest wavelengths and bandwidths (including transitions beyond the origin band) of possible carriers, but the controlled conditions in the laboratory also allow the derivation of oscillator strengths that are needed to estimate column densities. However, the sheer number of possible DIB carrier candidates to measure experimentally is so challenging — for example, there are more than 1.2 million PAH species with 100 or fewer C atoms — that targeted astronomical observations are needed to guide the selection of the most promising candidates by providing

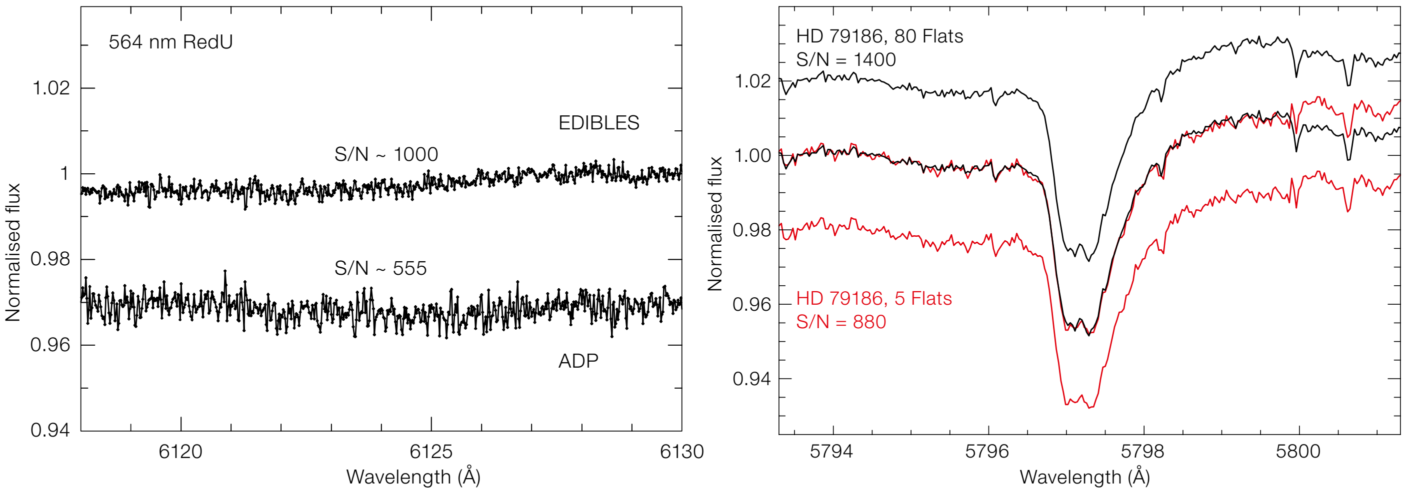


Figure 1. Left: A comparison between the results of the ESO Archive Data Products (ADP) and the EDIBLES processing pipeline (bin size: 0.02 Å). Figure from Cox et al. (2017), reproduced with permission from A&A. Right: The EDIBLES spectrum of HD 79186 around the 5797 Å DIB when using 80 flat fields (black) compared to the same observation using only five flat fields (red).

constraints on the carrier species. High-resolution observations of DIB line profiles can be used to estimate the size and geometry of the DIB carrier molecules as well as their excitation properties (see, for example, Marshall et al., 2015). Correlation studies and investigations of how DIB strengths change in different environments yield information about what drives variations in the DIB properties, such as the ionisation potential and chemical make up of the DIB carriers (see, for example, Ensor et al., 2017).

While there has been steady progress in the field over the years, most studies focus on the properties of a small number of DIBs, over particular wavelength ranges and in particular environments, or alternatively deal with large datasets and “average” properties of the DIBs (for example, Lan et al., 2015). Significant progress in the field can be expected from a high-quality, sensitive survey of interstellar features (DIBs, but importantly also known interstellar atoms and molecules) over a large spectral range and representing differing interstellar environments (Cami & Cox, 2014). The ESO Diffuse Interstellar Band Large Exploration Survey (EDIBLES) is such a survey.

EDIBLES

The aim of EDIBLES is to collect a large sample of interstellar spectra with UVES (Smoker et al., 2009) at high spectral resolution (R ~ 70 000 in the blue and 100 000 in the red arm), with a very high signal-to-noise ratio (median S/N ~ 500–1000 per target) over a large spectral range (3050–10420 Å), and with targets that represent very different physical conditions along the lines of sight. DIB targets are typically bright, early-type (O- and B-type) stars whose optical spectra contain relatively few stellar lines. In these spectra, the DIBs are more easily recognised and characterised. We selected bright (V < 8 magnitudes) O- and B-type stars, and constructed our sample so that we can probe a wide a range of interstellar environment parameters including interstellar reddening $E(B\text{-}V)$ ~ 0–2 magnitudes, visual extinction A_V ~ 0–4.5 magnitudes, total-to-selective extinction ratio R_V ~ 2–6, and a molecular hydrogen fraction $f(H_2)$ range ~ 0.0–0.8. Our final target list contains 114 objects of which 97 have been observed to date. Further details about the goals, objectives and sample selection can be found in Cox et al. (2017).

EDIBLES is an approved Large Programme that started in September 2014 (ESO period 94) under Programme ID 194.C-0883. The total allocated telescope time, excluding daytime calibrations, is 284 hours. As a programme, EDIBLES has been optimised, in terms of selected targets and observing strategy, to obtain observations when weather conditions are typically too poor for regular programmes (called “filler conditions”) and thus helps to optimise the use of the telescope. This makes it a less efficient process to reach a sufficiently high S/N, and we therefore require a large number of exposures.

A high S/N also requires a large number of flat field exposures. We have developed a custom data reduction procedure to process flat field frames so that we can attain the highest possible S/N (see Cox et al., 2017). Figure 1 illustrates how the addition of a large number of flat fields can greatly improve the quality of the resulting spectra. Using the same recipes and a higher number of flat field frames — even when obtained on different dates — can increase the S/N of other good-quality science observations in the UVES archive. In the red part of the spectrum, we could also improve and fine-tune the wavelength calibration using the large number of telluric lines available in our high-resolution spectra.

EDIBLES is unique in its combination of spectral resolution, wavelength coverage, sensitivity and sample size and this promises great advances in the field. As illustrated below, the high spectral resolution allows us to study individual DIB line profiles for a large number of DIBs, yielding size estimates for their carrier molecules when clear substructures are present. The high sensitivity facilitates studying both strong and weak DIBs simultaneously. This is important since laboratory spectra of typical DIB carriers often result in several transitions of comparable strength in the optical range, in contrast with the fact that no two DIBs have been found that undeniably originate from the same species (with the possible exception of the C_{60}^{+} DIBs). We expect that EDIBLES will reveal the first pair of perfectly correlating DIBs.

The large spectral coverage combined with the high resolution — which allows very good telluric corrections — will explore wavelength ranges over which few or even no sensitive DIB searches have ever been carried out. Furthermore, this range includes a large number of known interstellar absorption lines — due to atoms and small molecules such as CN or C_2 — which play an important role in EDIBLES. They enable us to accurately define the physical conditions in a large sample of lines of sight along which DIBs are measured, which is unprecedented on this scale. All these characteristics will enormously constrain the number of possible carrier molecules.

EDIBLES is also ideally suited for serendipitous studies that are not directly related to the DIBs. The large number of observations of O and B stars will turn out to be very useful for studies of massive stars and their stellar winds. Since our survey also includes observations of the same lines of sight at different epochs, the survey can also be used and complemented by archival data, to study small-scale variations in interstellar lines over time.

Resolved substructures in DIB line profiles

The high-resolution, high-S/N spectra of the EDIBLES survey reveal profile substructures in a large number of DIBs, and subtle variations in these profiles from one line of sight to another. A good example is the well-known triplet structure found in the 6614 Å DIB towards HD 170740 and HD 147165 (σ Sco), shown in Figure 2. We compare the DIB profiles, normalised to a common integrated intensity using an approach introduced by Marshall et al. (2015). It is notable that the absorption depths for the sub-peaks that are redwards and bluewards of the strongest central absorption differ for the two sightlines, and that the redward tail is stronger and more extended for HD 147165; this characteristic has been interpreted as arising from a stronger hot band contribution (Marshall et al., 2015).

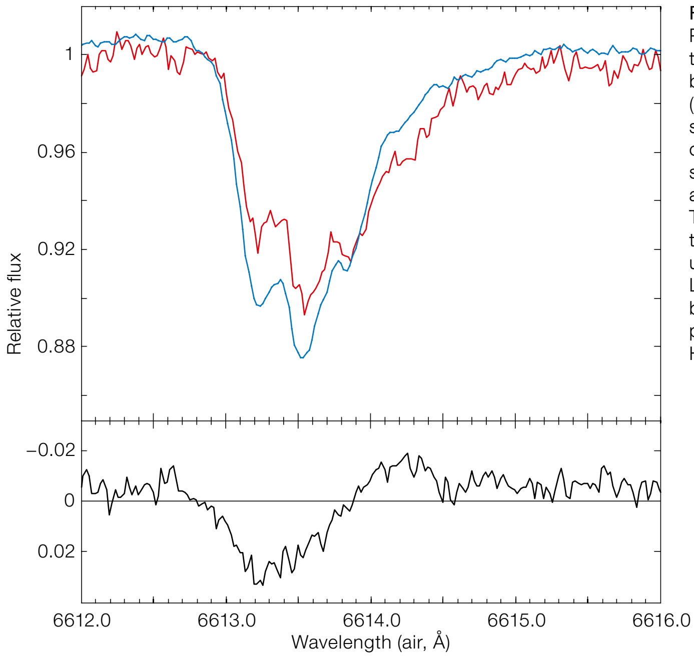


Figure 2. Upper panel: Profiles of the 6614 Å DIB towards HD 170740 (deeper, blue trace) and HD 147165 (broader, red trace). The spectra are normalised to a common integrated intensity and the ordinate values are those for HD 170740. The spectra are shifted to the interstellar restframe using K I radial velocities. Lower panel: The difference between the normalised profiles of the DIB in HD 170740 and HD 147165.

The details of the band profile depend on the rotational and vibrational temperatures and EDIBLES is designed to make progress in our understanding of precisely how these temperatures cause spectral changes. Indeed, the large numbers of EDIBLES sightlines sample the possible range of rotational and vibrational temperatures in interstellar clouds, and information on these temperatures can be derived from other molecular absorption lines in the EDIBLES spectral range. Modelling of these band profiles will thus provide the link between the observed spectral variations and the changes in temperature; in turn, this will greatly constrain the properties (for example, size and geometry) of the possible carrier molecules.

The C_2-DIBs

A particularly intriguing subset of the DIBs are the so-called C_2-DIBs (Thorburn et al., 2003); these are features that correlate especially well with the column density of C_2 molecules along the line of sight. This could imply that C_2-DIB carriers are chemically linked to C_2. Moreover, several C_2-DIBs appear in pairs that are separated by the same spacing of about 20 cm^{-1}, reminiscent of the spectroscopic signature of spin-orbit interaction in a linear molecule (Thorburn et al., 2003). Further constraints on the properties of the carrier will come from detailed analyses of the line profile shape of the C_2-DIBs. Since many of the C_2-DIBs are weak and high spectral resolution is required to resolve the profiles, substructure in the profiles of the C_2-DIBs was only reliably established for three to four C_2-DIBs, although asymmetries in observed profiles suggested that more of the C_2-DIBs could exhibit substructure (Galazutdinov et al., 2002).

In the EDIBLES dataset, we detect C_2 A-X rovibronic bands around 7700, 8800 and 10 100 Å in 25 sightlines, representing one of the largest samples to date for this important species (Cordiner et al., in preparation). This is another demonstration of the unique, extremely high sensitivity of our EDIBLES survey for the detection of weak spectral features. Excitation modelling of these C_2 spectra permits new insights into the temperatures and densities of diffuse molecular gas.

From this sample, we selected several EDIBLES targets that exhibit strong C_2 lines and that are "single clouds", i.e., there is only one dominant interstellar cloud along the direct line of sight to the target. For this sample of targets, we find that *all* C_2-DIBs have resolved structure in their profiles (Elyajouri et al., in

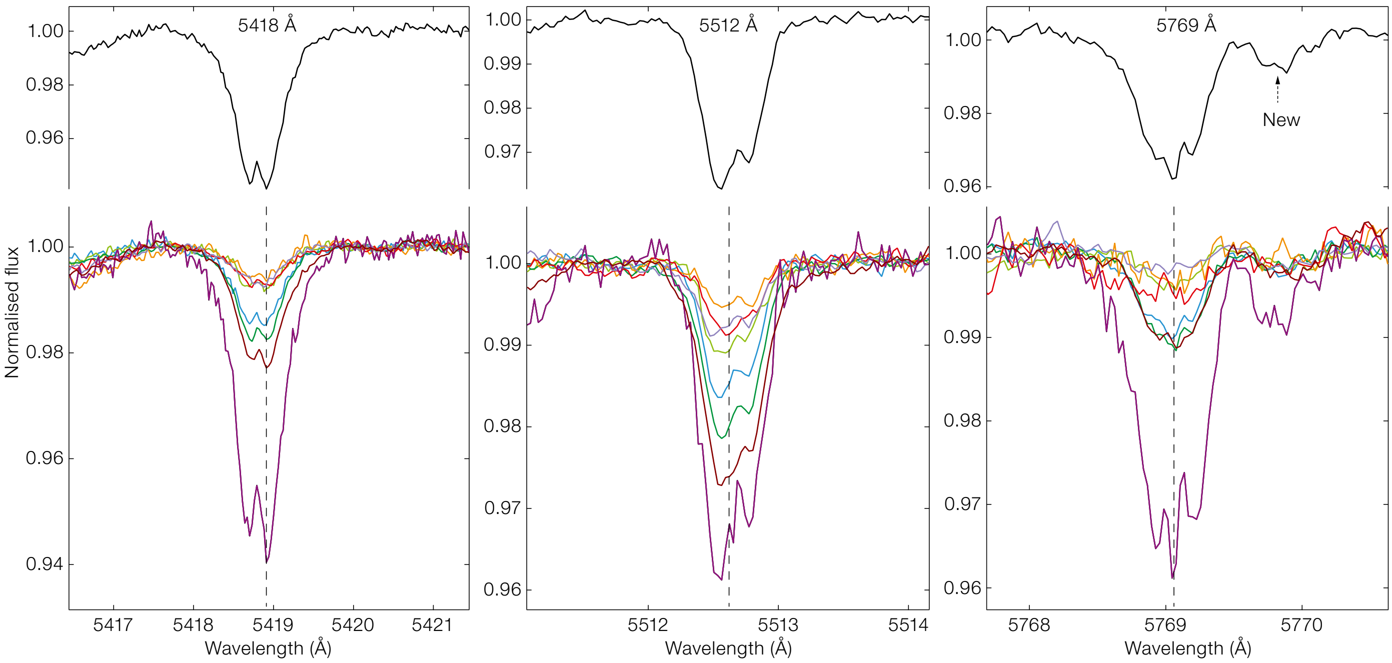


Figure 3. A few examples of the C_2-DIB profiles at 5418.91, 5512.62 and 5769.08 Å. Coloured lines display the individual sightlines. The black profile on top is the average normalised profile obtained by stacking the deepest bands of three single cloud targets.

preparation; Figure 3). The high resolution and S/N allow us to conclude with confidence that these substructures are neither telluric nor stellar in origin, and that the single-cloud nature of the targets eliminates multi-cloud confusion as well. These substructures are thus intrinsic to the C_2-DIBs and will reveal a lot about the properties of their carrier molecule(s).

The DIBs attributed to C_{60}^+

Foing & Ehrenfreund (1994) used laboratory measurements to predict that interstellar, gas-phase C_{60}^+ molecules would exhibit transitions near 9577 Å and 9632 Å. A dedicated search did indeed result in the discovery of two DIBs near those wavelengths with band characteristics that were expected for this species. However, the laboratory data that they used were obtained in cryogenic matrices in which the band positions and profiles may be affected. Obtaining a gas-phase spectrum at low temperatures has proven to be very challenging, but Campbell et al. (2015) succeeded in developing a technique to reliably measure the electronic spectrum under conditions that are appropriate for comparison with interstellar spectra. The central wavelengths of the two strongest bands in the laboratory experiments agree with the central wavelengths of the two DIBs, within uncertainties of ~ 0.1 Å. The laboratory spectrum furthermore exhibits three weaker bands and several authors have found evidence for these bands as well (for example, Walker et al., 2017; Cordiner et al., 2017).

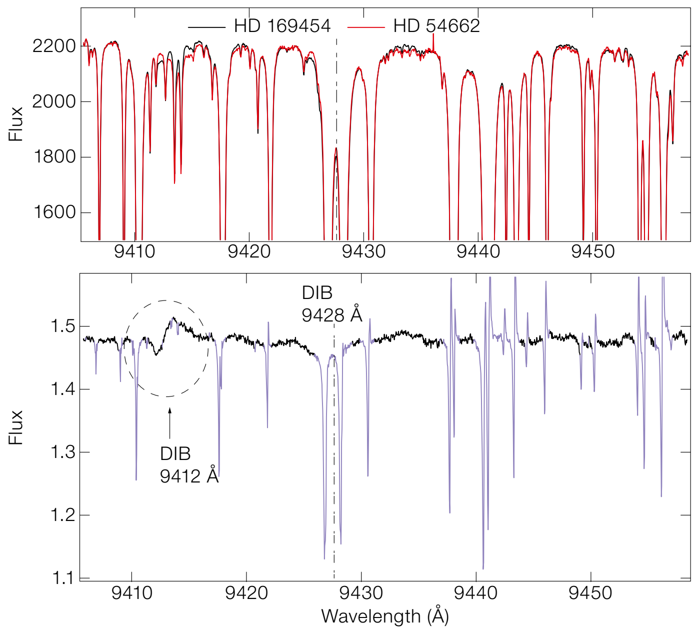
Unequivocally confirming even the presence of these weaker bands, however, is greatly complicated by the many strong telluric spectral features in the wavelength range over which the C_{60}^+ bands occur (Figure 4, top). Typically, the analysis is performed on a corrected spectrum, created by dividing out the telluric lines by means of a transmission model or the spectrum of a telluric standard star. However, with such strong telluric lines — also variable on short timescales — residuals are unavoidable and can result in severe artefacts. Figure 4 (middle) shows that, even when dividing out a spectrum with a very similar telluric profile (in this case of HD 54662), such residuals occur.

In the corrected spectrum, a clear feature shows up at 9412 Å; this is a known DIB that is unrelated to C_{60}^+. At the same time, at the expected position of the 9428 Å C_{60}^+ band, there appears to be a depression (somewhat masked by telluric residuals) and a Gaussian fit to that depression has an absorption depth that agrees with predictions, given the strength of the other C_{60}^+ bands. While this does not yet prove beyond any doubt that the 9428 Å DIB is present, the EDIBLES data support the identification of these DIBs with C_{60}^+ (Lallement et al., 2018).

The high spectral resolution of the EDIBLES data furthermore allows the study of some of the C_{60}^+ DIBs profiles despite the telluric contamination. For example, in the lower panel of Figure 4 we show how co-adding 79 individual observations of 43 different targets reveals the first evidence for an enormous amount of detail in the substructure of the strong 9577 Å C_{60}^+ DIB. This is possible because this DIB is only partially affected by telluric lines; the different interstellar cloud radial velocities then cause different parts of the band to appear in the "telluric-free" window (Lallement et al., in preparation). Small-scale variations in these substructures from one line of sight to another can then be used to study the fullerene molecular physics and the impact of the local physical conditions.

OH^+ and the cosmic ray ionisation rate

When Bhatt & Cami (2015) performed a sensitive survey of interstellar lines in the near-ultraviolet by stacking 185 UVES archival observations of reddened



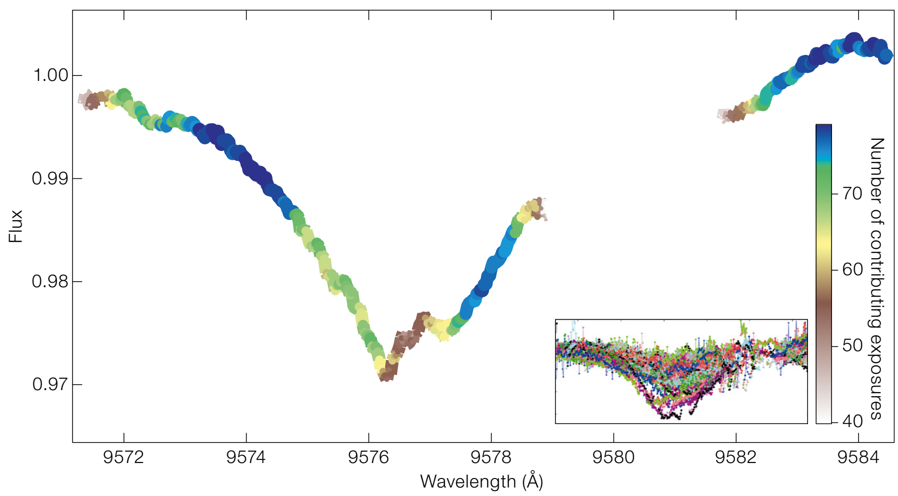


Figure 4. Upper: The EDIBLES spectra of HD 169454 and HD 54662 in the range of two weak DIBs: the 9412 Å DIB (unrelated to C_{60}^{+}) and a weak DIB at 9428 Å which is due to C_{60}^{+} (adapted from Lallement et al., 2018). Middle: The HD 169454 spectrum divided by the one of HD 54662. Lower: A composite showing partially resolved substructure in the strong 9577 Å C_{60}^{+} DIB. All fluxes are in arbitrary units.

targets, they discovered five new narrow interstellar features in the stacked spectrum that were too weak to be discerned in a single observation. Zhao et al. (2015) confirmed two of these features and identified them with transitions due to OH^+; they also found several more OH^+ lines in addition to the already well known line at 3583.76 Å. With several lines available that all arise from the ground state level, it is possible to accurately derive the corresponding population and infer the cosmic ionisation rate in diffuse interstellar clouds, something which has only been possible using space telescopes, and which yields comparable results.

The high S/N in the EDIBLES data and the wavelength coverage in the near-ultraviolet now show these very weak features almost routinely, and enable the calculation of the cosmic ray ionisation rate for a much larger sample than before, thus expanding the available line-of-sight information potentially also relevant for the DIBs analysis (Bacalla et al., in preparation; Figure 5). Indeed, the detection and analysis of such diagnostic molecules allow the community to interpret the DIB measurements within the context of their physical surroundings.

Variability in HD 148937

As an example of the potential for serendipitous discoveries, we show in Figure 6 a time series since 1995 of the He I line profile at 5876 Å in HD 148937, a magnetic Of?p star that is at the centre of the bipolar emission nebula NGC 6164. This object has been monitored for a long time, and small variations in stellar line profiles have been attributed to rotational modulation (Nazé et al., 2008). We noticed that the EDIBLES observations that were carried out in 2015 revealed a very different line profile compared to all previously published profiles (c.f. Figure 14 in Cox et al., 2017). Many more stellar lines show clear variations in their shapes and their wavelengths. A careful analysis reveals that this object is a massive spectroscopic binary, with a preliminary period of at least 18 years. The EDIBLES observations just happened to be acquired close to periastron passage, where effects on the spectrum would be most pronounced (Wade et al., in preparation).

Outlook

With EDIBLES, we have currently observed 97 early-type stars at high spectral resolution and at high S/N over a large spectral range. The first studies, some of which we have presented here, clearly show the enormous potential for new discoveries with this dataset. To ensure optimal exploitation and interpretation of this unique data set, the EDIBLES team is composed of researchers from a diverse community, including observational astronomers as well as experts in molecular astrophysics, interstellar physics and chemistry, and laboratory astrophysics. In addition to the scientific analyses, we have tested and demonstrated a recipe that is available to the community, which can significantly increase the S/N of UVES observations. The EDIBLES team is furthermore committed to providing the community with a catalogue detailing a large number of interstellar quantities for these sightlines — including DIB measurements. This catalogue is likely to serve as the DIB benchmark reference for many years to come. While the EDIBLES team focuses on the interstellar studies, the same data will also be fruitful ground for a diverse range of other projects, including stellar spectroscopy analyses. It is clear that EDIBLES will leave a significant legacy to the astronomical community at large.

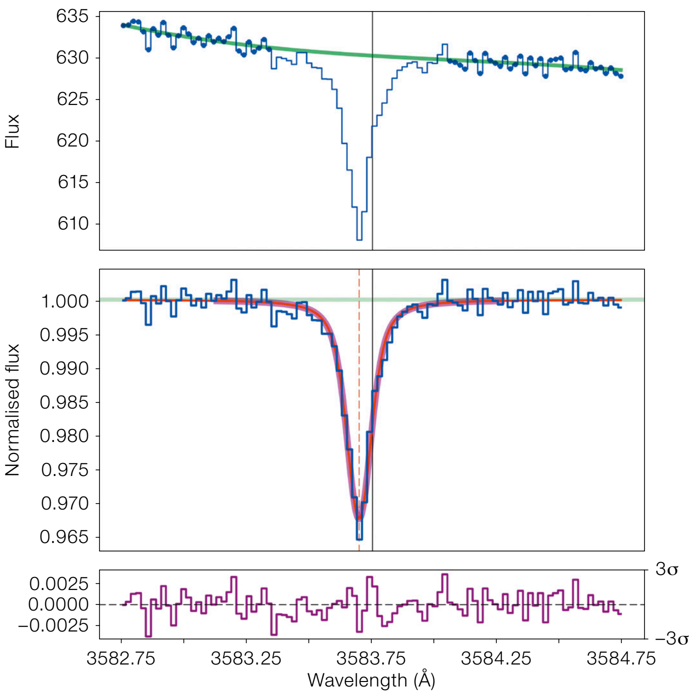
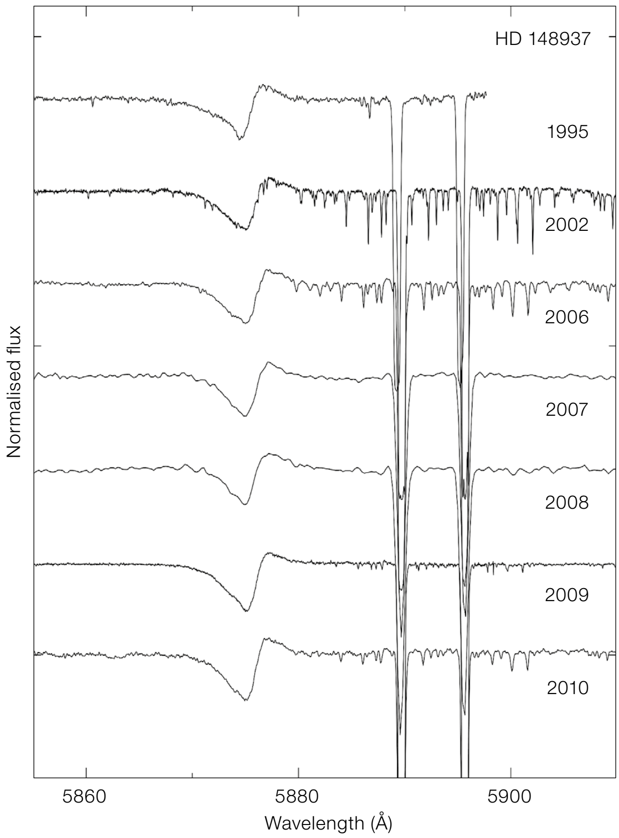


Figure 5 (above). The strongest OH^+ line at 3584 Å in the EDIBLES spectrum of HD 80558, with a Voigt profile fit.



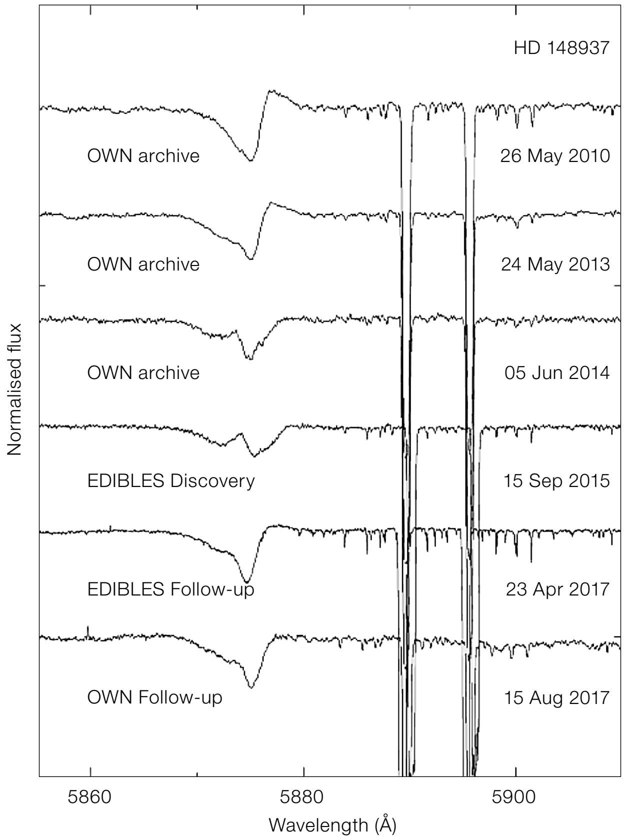


Figure 6. Upper Right: Archival observations showing the line profiles of the He I line at 5876 Å in HD 148937 between 1995 and 2010. Right: Archive observations from the Southern Galactic O- and WN-type stars (OWN) campaign (Barba et al., 2010) and EDIBLES observations of the same line between 2010 and 2017. Note how the character of the line profile changed markedly in 2014–2015 (Figure from Wade et al., in preparation).

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APEX Band 9 Reveals Vibrationally Excited Water Sources in Evolved Stars

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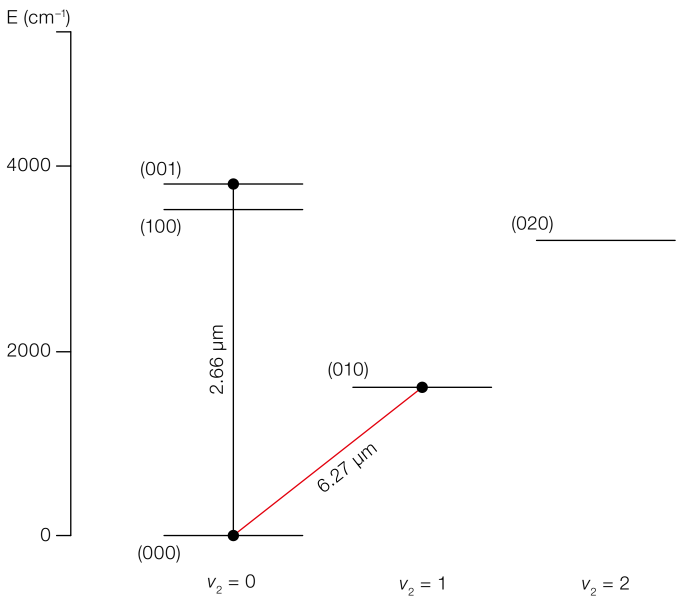

Figure 1. Vibrational energy diagram of water showing all states up to about 4000 cm^{-1}. The states are ordered along the horizontal axis according to the second vibrational state v_2. We show the two main vibrational transitions from the ground-state (v_1 = 0, v_2 = 0, v_3 = 0) to (010) and to (001) around 6.27 and 2.66 µm. The infrared transitions correspond to symmetric bending and anti-symmetric stretching of the water molecule. The 658 GHz rotational transition lies in the (010) state.

We have used the Atacama Pathfinder Experiment (APEX) telescope with the sensitive Swedish-ESO PI APEX (SEPIA) Band 9 receiver to discover several new vibrationally excited line sources of water at 658 GHz in the atmosphere of selected O-rich evolved stars. We have shown that this transition is masing and can be used to probe the gas in the dust formation zone or the wind beyond the central star. The 658 GHz line is widespread in evolved stars but most sources are weaker than about 300–500 Jy. However, some exceptional cases reach up to a few thousand Jy. New models incorporating several vibrationally excited transitions of water allow us to predict the physical conditions prevailing in 658 GHz sources. The strongest ones could be mapped with ALMA to study the small-scale clumpiness of the gas in the dust formation zone or, more generally, the stellar wind.

Water: a masing molecule and ubiquitous tracer of stellar evolution

Evolved objects such as asymptotic giant branch (AGB) and red supergiant (RSG) stars undergo strong mass loss (10^{-6} to 10^{-4} $M_{\odot}$ yr^{-1}) before they reach the white dwarf or supernova stage. Several mechanisms –0 for example shocks which can levitate stellar material, or radiation pressure on dust which drags the gas outwards – compete with gravity during the late stages of stellar evolution to shape circumstellar envelopes. Magnetic fields or nearby companions may also play a role in this shaping process. Owing to the presence of shocks and stellar winds, complex chemistry is observed in the extended atmospheres and the circumstellar envelopes of AGBs or RSGs (for example, Justtanont et al., 2012; Alcolea et al., 2013).

Among all of the molecules that have been identified towards evolved stars, water plays a prominent role because multiple infrared and radio wavelength transitions can be used to probe the physical conditions and kinematics in these stars. A first demonstration of the presence of water in the atmosphere of O-rich evolved stars was provided by the low-dispersion identification of vibrational transition bands in the 1–3 µm domain (for example, Spinrad & Newburn, 1965). To probe the layers of stellar atmospheres more precisely one needs to observe pure rotational transitions of H_2O in the radio domain with heterodyne receivers.

Strong 22 GHz emission from the $J = 6_{16}–5_{23}$ rotational transition of ortho-water in the (000) ground vibrational state was first reported by Cheung et al. (1969) toward Orion. Since then, 22 GHz emission has been observed in hundreds of young star-forming regions and evolved stars (for example, Kim et al., 2014). The 22 GHz line emission is often peculiar: the spectral features can be very narrow, polarised and time variable. In addition, Very Long Baseline Interferometry (VLBI) observations demonstrate that line brightness temperatures may reach about 10^{12} K in some RSGs. Such a high, non-thermal temperature is typical of maser action. Maser emission from various rotational levels above 640 K of the 22 GHz transition was also detected with various radio telescopes toward several evolved stars.

Most of these rotational lines of water can be explained by collisional pumping or by a combination of collisional and radiative pumping models. Recently, Gray et al. (2016) included energy levels up to the (020) vibrational state lying some 4500 K (about 3150 cm^{-1} or 3.17 µm) above the ground vibrational state (Figure 1). Because of the large near-infrared flux density in evolved stars, rotational transitions in the populated (010) and (020) vibrational states should be detectable and can be used to probe the physical conditions and dynamics of specific regions around stellar sources more thoroughly. Several rotational transitions of H_2O in the (010) state have been observed in the radio domain (see Table 1 in Gray et al., 2016). However, these lines tend to be weak, with the exception of the transition discussed here; the $J = 1_{10}–1_{01}$ rotational transition of ortho-water at 658 GHz lies in the (010) state about

Source name	Variabilty	Reference	Source name	Variability	Reference
WX Psc	OH/IR	5	S Vir	Mira	1
R Aql	Mira	4	W Hya	Mira	3, 2, 1, 5
o Ceti	Mira	5,2	RU Hya	Mira	2
R Cet	Mira	1	RX Boo	SR	3
R Hor	Mira	2	S CrB	Mira	3
RT Eri	Mira	2	V351 Nor	LP variable	1
IK Tau	Mira	4, 5, 2	IRAS 15568-4513	IR source	1
U Men	SR	1	U Her	Mira	3
R Dor	SR	5, 1	V446 Oph	SR	1
R Cae	Mira	1	V1006 Sco	SR	1
IRAS 05052-8420	AGB	1	AH Sco	RSG	2
TX Cam	Mira	4, 5	RW Sco	Mira	1
T Lep	Mira	1	V1019 Sco	SR	1
U Dor	Mira	1	V4201 Sgr	SR	1
S Pic	Mira	1	VX Sgr	RSG	3
R Oct	Mira	1	RAFGL 5552	RSG?	1
U Ori	Mira	4	R Aql	Mira	4
L2 Pup	SR	1	V342 Sgr	Mira	1
V578 Pup	Mira	1	GY Aql	SR	1
VY CMa	RSG	3, 2, 4, 8, 9	V2234 Sgr	AGB	1
OH231.8+4.2	PPNebula	6	X Pav	SR	2
KK Car	Mira	1	T Mic	SR	1
RW Vel	Mira	1	NML Cyg	RSG	3, 7
RS Vel	Mira	1	IRAS 20541-6549	AGB	1
IW Hya	Mira	1	R Peg	Mira	1
R Leo	Mira	3, 4	R Aqr	Mira	1
IRAS 10323-4611	C star	1	R Cas	Mira	4, 5
R Crt	SR	3			
RT Vir	SR	3, 2	OH26.5+06	AGB	5
R Hya	Mira	4, 2	RAFGL 5379	AGB	5

Table 1. A complete list of stars detected in the vibrationally excited line of ortho-water at 658 GHz (as of September 2017). Stellar sources are ordered by right ascension with two weak detections added at the end. Mira, RSG and SR stand for Mira-type, red supergiant and semi-regular variability respectively. OH/IR variability means the O-rich AGB star has an unknown or uncertain period of variability. References are: 1 This work; 2 Baudry et al. (2018); 3 Menten and Young (1995); 4 Hunter et al. (2007); 5 Justtanont et al. (2012); 6 Bujarrabal et al. (2012); 7 Teyssier et al. (2012); 8 Alcolea et al. (2013); 9 Richards et al. (2014).

1640 cm^{-1} or 2360 K above the ground-level, and was first detected in variable stars and two RSGs (Menten & Young, 1995).

Widespread 658 GHz line emission toward evolved stars

Several years after the discovery by Menten and Young (1995), observations using the Submillimeter Array (SMA) and Herschel Space Observatory with the Heterodyne Instrument for the Far-Infrared (HIFI) expanded the number of sources detected at 658 GHz to 19 evolved, variable stars (Hunter et al., 2007; Justtanont et al., 2012). Weak emission was also detected with HIFI from two AGB stars (Justtanont et al., 2012) and from one protoplanetary nebula (Bujarrabal et al., 2012). These observations suggested that 658 GHz stellar sources are widespread. Along with our models, which predict that the 658 GHz line can be strongly masing, this suggests that the Atacama Large Millimeter/submillimeter Array (ALMA) could map the most interesting sources.

With this in mind, we built a small catalogue consisting of nearly 100 candidate and known 658 GHz southern sources. The sample is based on stars with known H_2O (22 GHz) and SiO (43 and/or 86 GHz) maser emission above a fixed flux density limit of ~ 50 Jy. SiO emission is important because it is present in many O-rich evolved stars, and SiO and 658 GHz H_2O excitation levels are close to each other (~ 1800 and 2360 K, respectively). A large fraction of our selected sources comes from a homogeneous sample that was simultaneously observed in SiO and H_2O (22 GHz) by Kim et al. (2010). Additional sources were added from the published literature using the same selection criteria in order to improve the coverage in declination.

We used the APEX telescope, using the dual-sideband and dual-polarisation Band 9 Swedish-ESO PI receiver for APEX (SEPIA; Belitsky et al., 2017). The receiver was tuned to place the 658 GHz water line and the J = 6–5 line of ^{13}CO at 661 GHz in the lower sideband where the atmospheric transparency is better. APEX is the only telescope other than ALMA that is currently equipped to observe at 658 GHz.

In our first observing campaign (from April to June 2016) we used SEPIA Science Verification time to observe nine AGB stars and one supergiant source. All ten sources were detected, half of which were new discoveries (Baudry et al., 2018). In a second observing campaign (from July to September 2017), 39 other sources from our sample of late-type stars were observed with the fully commissioned SEPIA receiver. Both runs had good observing conditions with precipitable water vapour below 0.7 mm. A total of 31 new 658 GHz sources were detected (most of them are shown in Figure 2). Our 2016 and 2017 results more than double the number of stars known to exhibit 658 GHz emission, demonstrating that this water transition is widely excited in evolved O-rich stars. All our data were reduced using the Continuum

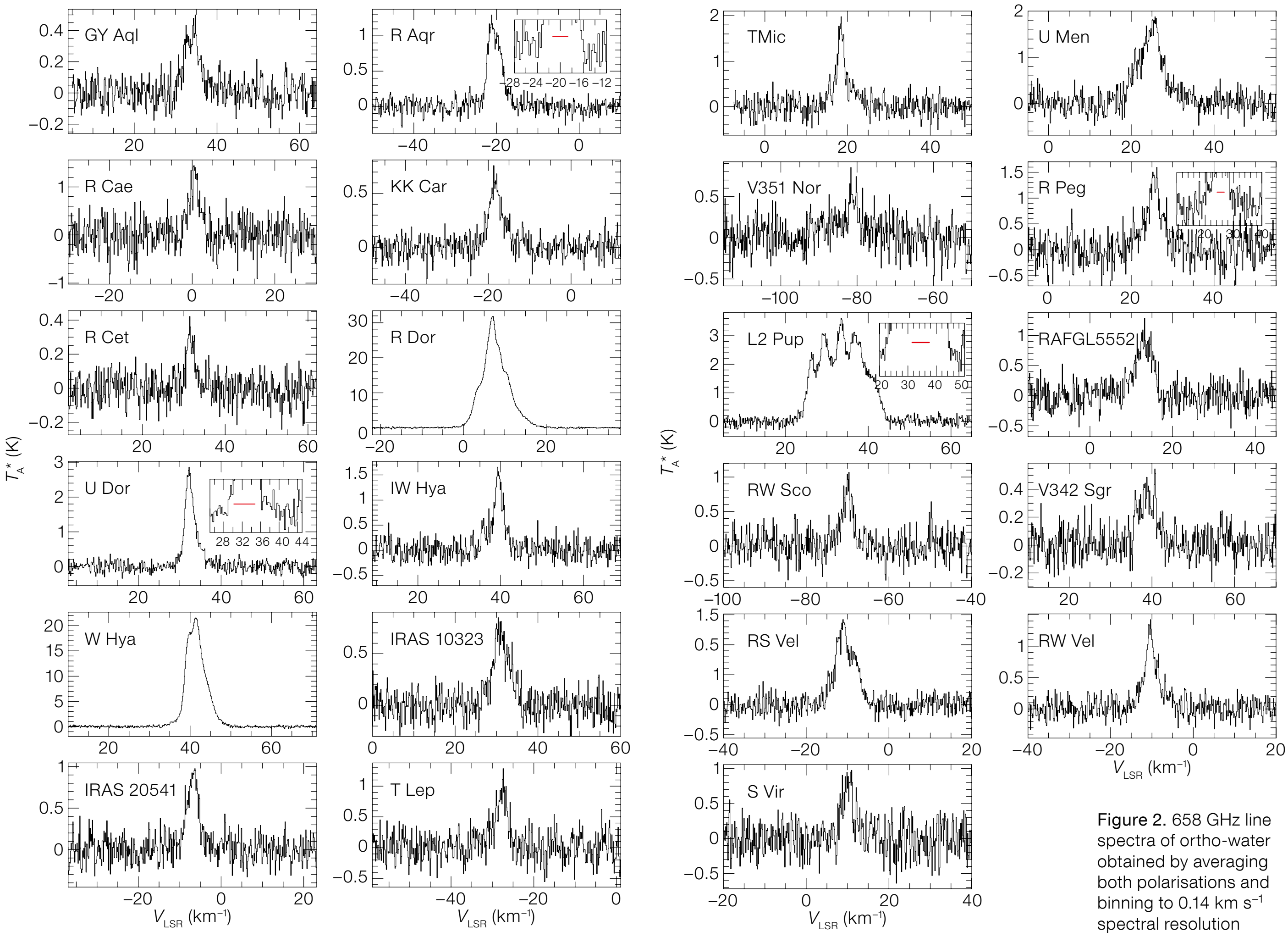

Figure 2. 658 GHz line spectra of ortho-water obtained by averaging both polarisations and binning to 0.14 km s^{-1} spectral resolution towards O-rich stars observed with APEX in 2017; one of the stars IRAS10323-4611 is C-rich.

and Line Analysis Single-dish Software (CLASS) software package[1].

The 658 GHz line profiles are smooth and centred close to the stellar velocity. However, the strongest sources can exhibit asymmetrical line profiles and are likely due to maser emission as explained below. The line widths at half intensity are a few km s^{-1}, with the exception of the supergiant VY CMa (~ 11 km s^{-1}) and the peculiar AGB L2 Pup (~ 14 km s^{-1}). The observed peak line intensities in Figure 2 are given in terms of the antenna temperature, T_A*, and corrected for absorption due to the Earth's atmosphere, which allows them to be converted into source flux densities. Observations show variations in T_A* from 0.3–0.4 K for the weakest sources, up to about 31.8 K for R Dor. We derive a flux density to

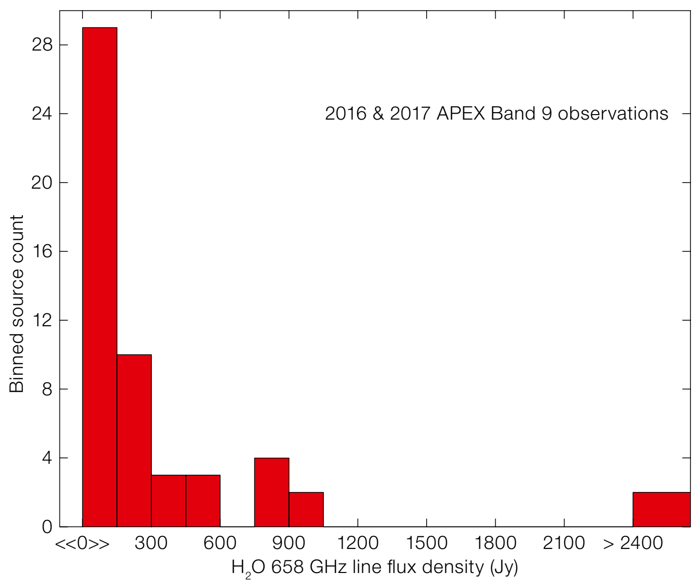

Figure 3. Histogram showing the 658 GHz line flux density of ortho-water for all sources observed with APEX in 2016 and 2017. The first bin from <<0>>–150 Jy starts at the 3-σ level, at ~ 29 Jy.

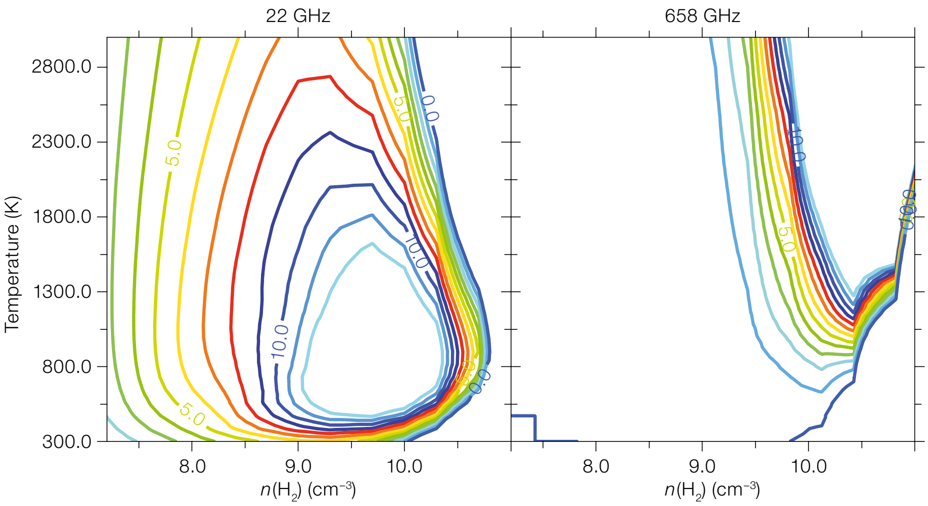

Figure 4. Maser negative optical depth contours for the 22 and 658 GHz lines in the kinetic temperature versus H_2 density plane according to Gray et al. (2016) modelling. Contours are equally spaced up to the maximum value of 12.

antenna temperature conversion factor of 120 (± 10) Jy K^{-1} from 2017 (unresolved) Uranus observations. The observed source flux density varies from ~ 40–3800 Jy, a broad range which partially reflects different distances to the sources, and is partially due to different maser line amplification processes or stellar activity. Nearly all sources are weaker than 300–500 Jy. Figure 3 shows the histogram of 658 GHz flux density for all of our sources, which has a peak below 150 Jy. Table 1 lists the variability characteristics of all evolved stars for which there are 658 GHz water line detections (as of September 2017).

On the masing nature of the 658 GHz emission

We do not think that the 658 GHz line is thermally broadened and excited for several reasons. First, the line width at half-intensity (which is broader than the expected 2–2.5 km s^{-1} thermal line width) remains small compared to the typical 10 to 20 km/s line width of the ^{13}CO, J = 6–5 line requiring hot gas conditions (compared to low-J CO emission). And, for most stars, the 658 GHz line width at half-intensity remains small compared to the low-J CO line width. Secondly, since the flux density of the 658 GHz transition can reach several thousand Jy we may infer that the line brightness temperature T_b(658) is well above the gas kinetic temperature (though our single dish observations only provide weak constraints).

In the unique case of VY CMa Richards et al. (2014) were able to map the 658 GHz emission with ALMA and identify gas "clumps" with brightness temperatures above 0.3–4 × 10^7 K. The nearly contemporaneous 22 and 658 GHz observations of Menten and Young (1995) can be used to constrain T_b(658) in other evolved stars. Assuming that both emissions at a given spectral velocity are excited in comparable gas volumes, we expect values of T_b(658) ~ 10^4–10^{10} K from 22 GHz observations of AGBs. This clearly indicates suprathermal emission and maser action for VY CMa and AGBs.

Finally, the multi-level, radiative transfer calculations applied to physical conditions and material slabs typical for evolved stars show that the 658 GHz line can be inverted and masing (Gray et al., 2016). In Figure 4 we compare the physical conditions leading to 22 and 658 GHz maser emission. Negative 658 GHz opacities as high as 10 are reached for kinetic temperatures from 1000–2800 K or over and for densites of ~ 10^{10} cm^{-3}, suggesting layers of material that are relatively close to the stellar photosphere.

Figure 4 also shows that the loci of inverted 22 GHz line emission are broader than those at 658 GHz. This is expected for a transition which is both collisionally and radiatively excited and thus easily detected in a variety of physical environments. Along with the high-energy levels at 658 GHz, it appears likely that the 658 GHz line is formed in layers close to the photosphere. The 658 GHz map of VY CMa (Richards et al., 2004) showed that the broad aggregate line profile is made up of several spatially and spectrally distinct gas clumps. The narrower spectral features are distributed within 50–250 milliarcseconds of the central star in a region where SiO masers are also present.

It is possible to prove indirectly that the 658 GHz emission is excited close to the star by comparing the 658 GHz velocity extent at "zero" intensity with the same quantity for the SiO maser emission at 86 GHz in the first vibrational state for a small sub-sample (Baudry et al., 2018). This can be justified because: a) the SiO v = 1 state energy is around 1800 K and close to the (010) vibrational state of the 658 GHz line; b) the emission peak velocities of both maser lines are close to each other; and c) VLBI observations indicate that SiO masers are formed within ~ 5 R* of the central object. The loose correlation found (see Figure 5) suggests that both masers are excited in similar environments close to the central star, but this should be confirmed with a larger sample.

In a few stars, the 658 GHz line width to 'zero' intensity (defined as the width down to 2- to 3-σ spectral noise) is comparable to that measured for CO, which traces the circumstellar envelope expansion. In four stars — R Aqr, U Dor, L2 Pup and R Peg — the 658 GHz low-level emission is broader than the corresponding CO velocity extent; see horizontal, red bar in Figure 2 for CO, J = 2–1 velocity extent from Groenewegen et al. (1999), Kerschbaum & Olofsson (1999) and Winters et al. (2002). This low-intensity emission is unlikely to trace the envelope expansion in regions that are cooler than required to excite the 658 GHz line. On the other hand, it could be related to gas acceleration close to the central star and/or perhaps to shocks; this is also supported by 658 GHz filaments observed by ALMA in VY CMa. Even if the bulk of the 658 GHz emission is masing we cannot exclude the possibility that the low-intensity radiation is due to weak thermal excitation of the gas.

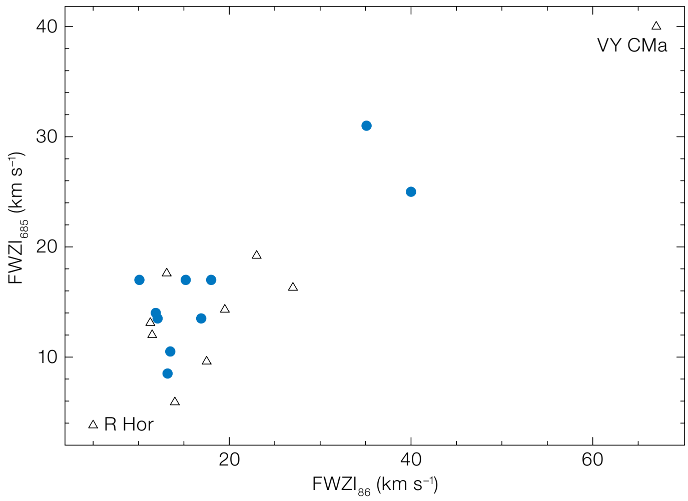

Figure 5. Full width at zero intensity (FWZI) at 658 GHz (vibrationally excited H_2O) *versus* FWZI at 86 GHz (SiO, v = 1 maser) for 10 sources (triangles) observed in Baudry et al. (2018) and 10 additional sources. The R Hor and VY CMa labels mark the two ends of the observed loose correlation.

Time variability, light amplification and future plans

Molecular line masers, especially the 22 GHz H_2O line, often exhibit time variability and narrow spectral features, resulting from the population inversion and radiation amplification mechanisms. These properties are not immediately obvious with our single-dish observations of the 658 GHz line. In two well-studied cases, VY CMa and W Hya, which have been observed over more than 20 years, the emission line profiles have remained stable and asymmetric, though there is a regular decline of the peak intensity in the VY CMa observations. In Baudry et al., (2018) we also showed that, by comparing the ratio of the H_2O(658) to ^{13}CO(6–5) integrated intensities nearly six years apart, we could not reconcile the measurements in three stars (o Ceti, IK Tau and W Hya). This suggests time variability at 658 GHz and, indirectly, maser action — since the high-*J* ^{13}CO broad line profile related to circumstellar expansion should not change rapidly.

The 658 GHz line width of individual masers depends on the light amplification regime within the material in which the H_2O population is inverted. If the radiation grows with the exponential of the 658 GHz opacity as expected for unsaturated masers, we may observe rapid time variability and line features that are smaller than the local thermal line width. At the other extreme, maser saturation corresponds to an intrinsic maximum luminosity resulting in little or no time variability and the individual maser line features may be as broad as the local thermal width. The 658 GHz single-dish observations do not show spectral features as narrow as the expected thermal line widths because the multiple 658 GHz velocity–blended components forming the overall line profile within the 9-arcsecond beam of APEX remain unresolved. These components can only be separated by mapping their emission (for example, VY CMa; Richards et al., 2014).

Our APEX results suggest that strong 658 GHz line sources could be mapped with ALMA to reveal the details of the kinematics and the small-scale clumpiness of stellar winds within the dust formation zone and beyond. In the case of the supergiant VY CMa, ALMA showed that the 658 GHz emission extends further out of the dust formation zone. However, we do not know if this property, which likely traces shocks in the stellar envelope, is specifically due to its exceptionally strong winds (VY CMa's mass loss rate ~ 2×10^{-4} M yr^{-1}). 658 GHz images obtained at different epochs for some sources could also tell us how gas clumps evolve with time, which ones show variable activity, and more generally, how stellar winds evolve. Finally, we note that this transition may be suitable for ALMA Band 9 phase calibration, given the relatively simple line shapes and strength of the 658 GHz emission in stars for which coordinates are well known. Compact (< 0.35 arcseconds) and strong 658 GHz emission was detected towards the massive protostar Orion Source I in the Orion KL region (Hirota et al., 2016), and could also be used for phase calibration.

Acknowledgements

Our data were acquired with the APEX telescope equipped with the Swedish-ESO Band 9 receiver. APEX is a collaboration between the Max-Planck-Institut für Radioastronomie, ESO and the Onsala Space Observatory. We warmly thank the APEX staff who carried out the APEX SEPIA Band 9 observations.

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Links

[1] CLASS software package: http://www.iram.fr/IRAMFR/GILDAS

ESO/D. Mégevand

ESO/Nikki Miller

Upper: The ESPRESSO instrument achieved first light combining the light from all four 8-metre Unit Telescopes in February. The ESPRESSO team marks the occasion with the ESO Director General here.

Lower: Students take part in ESO's Winter Astronomy Camp 2017, which took place between 26 December and 1 January.

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New President of Council

Willy Benz[1]

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Alessandro Della Bella

Is there an astronomer who has not dreamt of being actively involved in the development of world-class astronomical facilities, including the building of the largest telescope ever? This is the fantastic opportunity that has been offered to me by the ESO Council following my election as President of this body in late 2017. This is an incredible honour, a huge responsibility and the cause of some anxiety, but I also feel a genuine eagerness to get started. So many challenges lie ahead, but the organisation is strong thanks to several factors: its extraordinary staff; the dedication of Member States to work for its success; and the strong engagement of the community at large at all levels. These constitute a strong recipe for success, and are good reasons for me to be confident.

I grew up in Neuchâtel, a small town in the French-speaking part of Switzerland, where I studied physics. I later obtained my PhD in astronomy under the guidance of Michel Mayor at the University of Geneva and then moved to the USA on a one-year fellowship from the Swiss National Science Foundation. I ended up staying for thirteen years — life is unpredictable. A postdoctoral position at Los Alamos National Laboratory followed, and I then became junior faculty at Harvard University and senior faculty at the University of Arizona. My scientific interests were quite broad, ranging from understanding the origin of our Moon to the physics of supernova explosions. Eventually, I focused on the origin and evolution of planets within and outside the solar system.

In 1997, I was offered a professorship in the Physics Institute of the University of Bern and my whole family returned to Switzerland. While my wife and I had left home with two suitcases and our 20-month old daughter Sophie, we returned with one container, two additional daughters, Florence and Melanie, Coal the dog, and Leo the cat!

Unsurprisingly, Switzerland is quite different from the USA and it took us all some time to re-adjust. After a few years, I became director of the Physics Institute, a job that I held for thirteen years. During that time, I also got involved in my first ESO project, the High Accuracy Radial velocity Planetary Searcher (HARPS). More recently, I had the chance to join new ESO projects such as the Échelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO), the Near Infra Red Planet Searcher (NIRPS) and even the proposed Extremely Large Telescope (ELT) instrument, HIRES. Having started as a theorist, I didn't play a leading role in these projects but supported their construction with the help of our engineers.

In 2008, a few colleagues and I started playing with the idea of building the CHaracterising ExOPlanets Satellite (CHEOPS), a small Swiss satellite dedicated to measuring the radii of known planets orbiting bright stars using the transit method. Unfortunately, a one-year feasibility study concluded that the mission was too ambitious to be carried out by Switzerland alone.

The project took on a new dimension with the decision in 2012 by the European Space Agency's (ESA) Space Programme Committee to establish small-class missions. As chairman of the Space Science Advisory Committee, I had carefully followed the discussions leading to the decision and decided to submit our idea in response to the call. We eventually assembled a consortium and submitted the proposal in June 2012. Our proposal was selected against 25 other proposals that October, and I was subsequently appointed Principal Investigator of the mission, which involves institutes in 11 ESA member states. Life is unpredictable. Unsurprisingly, this project has taken a lot of my time during the last five years, but the launch is scheduled for early 2019 and science is now on the horizon!

While all these activities were going on, we managed to establish the Center for Space and Habitability at the University of Bern in 2011, and, in 2014, a National Centre for Competence in Research (NCCR) in planetary sciences, called PlanetS, of which I am now the director. Bringing together all the key players in this field across Switzerland, this centre has provided scientists in the country with new research opportunities, including the means to participate in ESO instrumentation projects (for example, the Enhanced Resolution Imager and Spectrograph [ERIS] and NIRPS).

My excursion into the European Space Programme has not prevented me from keeping close ties with ESO. It is simply impossible to move away from such an organisation! Eventually, I had the privilege of serving on two visiting committees, and in between, to chair the Science and

Technical Committee over the period during which Laurent Vigroux and then Xavier Barcons presided over Council. These last three years, I have been one of the two members of Council representing Switzerland — a time during which I could learn the inner workings of the Council and appreciate the exemplary leadership provided by its President Patrick Roche.

I don't think it will come as a surprise to anyone to hear that the organisation is facing significant challenges. These result from embarking on the building of the ELT, the largest telescope ever conceived, while at the same time keeping the existing world-class observatories (La Silla Paranal Observatory and the Atacama Large Millimeter/submillimeter Array) operational, up-to-date and at the forefront of ground-based astronomy.

The challenges are not solely of a financial nature. Just two examples include finding staff with the specific qualifications needed, and managing large projects across the world. Furthermore, in a financially constrained environment, the workload and the associated stress on everyone, from the Director General to all the staff, including everyone's families, have risen significantly. The Director General and I are aware of this situation and, together with Council, we will regularly revisit and monitor these issues, including the general work-life balance at ESO, over the coming years.

We have given ourselves fantastic challenges that we now must overcome. We have prepared ourselves to the best of our abilities to tackle them effectively and in a timely manner. With the organisation, the Member States and the community we have assembled a winning team. I am looking forward to working with everyone to continue building this world-leading astronomical organisation.

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Review of the Last Three Years at ESO

Patrick Roche[1]

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I completed my three-year term as President of the ESO Council at the end of December 2017. This is therefore an appropriate point at which to review Council's activities over this period and to reflect on how ESO's programme has moved forward.

ESO is an evolving organisation, in terms of its Member States as well as its scientific and technical programmes and its organisational structure. Poland became the fifteenth Member State when the formal accession process was completed in 2015. In 2017, Australia entered into a strategic partnership with ESO, providing Australian astronomers with access to the La Silla–Paranal facilities for a decade, whilst opening up the possibility of moving towards full membership in due course. There was also good progress with the accession of Brazil through its parliamentary process in 2015, but the procedures have not been completed.

Working with the Director General, Council sets the policy and strategy for ESO while Council delegates work closely with their ministries, science communities and the ESO executive towards realising the agreed strategy. Council normally meets four times a year, with two formal meetings usually held at the Garching HQ and two less formal Committee of Council meetings, which are often hosted by a Member State. I am very grateful to the hosts of these meetings, which afford opportunities to meet representatives of the scientific communities and funding agencies, and to learn more about national activities as well as undertaking Council business.

A real strength of ESO is the support and commitment to the programme provided by the Member States, who have agreed not only to fund the ELT construction whilst maintaining the current facilities as forefront scientific instruments, but also to provide support for the technology, instrumentation and science programmes in national institutes and organisations. This support is being provided at a time when many Member States have constrained domestic programmes, and reflects the importance placed on ESO's facilities and the close collaborations with the national communities.

In addition to the Council meetings, I have attended a number of other ESO meetings and workshops and have valued the opportunities that they provide to meet staff and learn more about the extent and depth of ESO's activities. I have especially valued attending the ESO Annual Overview, which reveals the strength and depth of activities across the organisation and the commitment of the staff to excellence.

There are many aspects of ESO's programme to note and celebrate. The ESO press releases, webpages and editions of the Messenger showcase many of the outstanding science results that have been obtained, but I want to highlight a few of them here:

– Commissioning activities of the Very Large Telescope (VLT) second-generation instruments, KMOS, SPHERE and MUSE, have been completed, and are currently ongoing for several others (for example, GRAVITY, MATISSE and ESPRESSO). These instruments equip the telescopes with an unparalleled suite of powerful instruments for astronomical discovery. The ensuing scientific results continue to push our understanding of a wide range of astronomical objects and phenomena. The development of the Adaptive Optics Facility continues to progress, and the introduction of further operational modes will be very important in gaining experience for future developments and operating ESO's Extremely Large Telescope (ELT).

– The modification and development of the infrastructure in the combined focus of the VLT in preparation for the second-generation VLTI instruments and the Échelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) have been completed. Initial results from the adaptive optics assisted, two-object, multiple-beam-combiner VLTI instrument GRAVITY indicate that precision astrometric measurements that will open up new opportunities are within reach, with new capabilities imminent when MATISSE and ESPRESSO are commissioned.

– The completion of the Residencia for the Atacama Large Millimeter/submillimeter Array (ALMA) and its handover for operations in 2017 marked the completion of ESO's contributions to ALMA construction. The stunning science results obtained to date demonstrate that ALMA is indeed the transformational facility we hoped it would be and that it will meet its design goals. A vision for the further development of ALMA's capabilities over the next decade has been agreed by the ALMA Board; it will lead to greater instantaneous bandwidth and higher sensitivity as a high priority, guaranteeing that ALMA will continue to meet community expectations.

– New instruments for the 3.6-metre and NTT telescopes at La Silla have been selected, securing their futures for the next decade and ensuring that La Silla remains the natural place to host national facilities and experiments.

– The education and Public Outreach programmes have continued to showcase the output from ESO's observatories and to encourage participation in science and technology. A very visible sign of this activity is the Supernova Planetarium & Visitor Centre. The building has been completed and the exhibits are now being installed in preparation for operation in 2018. The Supernova building resulted from a very generous donation by the Klaus Tschira foundation and is a landmark facility that will further extend ESO's reach.

– Following approval of the first phase of the construction of the ELT by Council at the end of 2014, ESO has moved forward with contracts for the infrastructure and the major optical and mechanical structures of the telescope. At the same time, Council has maintained the momentum of the project by agreeing a schedule with first light in 2024 and adding all of the primary mirror segments to the approved first phase of the telescope. The ELT is a very challenging project, but progress to date has been impressive. Council is fully supportive and is looking forward to the beginning of the site works on Cerro Armazones early in 2018.

There have been many other achievements, including instrument upgrades, anti-obsolescence programmes, software developments, upgrades to administrative processes, amendments to procurement rules and staff benefits and regulations, approval and monitoring of budgets, and interactions with potential new Member States and other institutes and organisations around the world. All of these activities are essential in underpinning ESO's mission to provide front-line observational capabilities and to foster cooperation in astronomical research. They rely on the talent, dedication and hard work of many people at ESO and at institutes and organisations in the Member States and beyond, as well as the support and cooperation of the Republic of Chile.

I would like to take this opportunity to thank everyone who has contributed to ESO's outstanding programme over the last three years. I have worked closely with many dedicated people and have benefited greatly from their support and advice. Tim de Zeeuw completed his ten-year mandate as Director General at the end of August 2017. This occasion was marked by a conference that highlighted ESO's achievements over the last decade. It was a truly impressive account of ESO's activities and its position as the world's leading observatory, as well as Tim's contributions to that. Xavier Barcons has taken over as Director General and is working hard to ensure that ESO's programmes remain on track and that the organisation continues to perform at the highest level.

I am delighted that Willy Benz has taken on the role of Council President, and I believe that the ESO programme is in good shape as well as in very good hands.

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Report on the ESO Workshop

QUESO: Submillimetre/Millimetre/Centimetre *Q* & *U* (and *V*)

held at ESO Headquarters, Garching, Germany, 25–27 October 2017

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Polarised emission encodes essential physical information about many components of the Universe, ranging from dust grains and magnetic fields in molecular clouds, protoplanetary discs and evolved stars, through to the formation and propagation of relativistic outflows in Active Galactic Nuclei, and to the effects of inflation and primordial gravitational waves on Cosmic Microwave Background (CMB) anisotropies. The aim of this workshop was to bring together current and future ALMA users, observatory calibration experts and software developers from a broad range of research fields making use of polarimetric techniques in the frequency range between approximately 5 and 1000 GHz. This range was deliberately restricted in order to focus attention on common problems and to promote cross-fertilisation between different subject areas. The meeting provided an opportunity for the polarimetric community to develop collaborations, understand the latest technological developments and decide on common priorities for the future.

Figure 1. Participants at the QUESO Workshop photographed in front of the ESO Library.

Observing centimetre- or millimetre-wave polarised radiation at very high angular resolutions and sensitivities typically involves the use of interferometric techniques. Modern instruments can now enable full polarisation imaging at unprecedented sensitivity over wide instantaneous bandwidths. Polarisation observations have become routine at the Karl G. Jansky Very Large Array (JVLA) as well as other modern observational facilities in the centimetre, millimetre, and submillimetre bands, and they will increasingly become important for the Atacama Large Millimeter/submillimeter Array (ALMA). It is particularly exciting to note that ALMA's excellent site will allow interferometric polarisation observations to be made at frequencies approaching 1 THz for the first time.

The meeting began with two extended presentations by George Moellenbrock and Ivan Marti-Vidal on polarimetric techniques for high-frequency interferometry. These presentations summarised the techniques of interferometric polarimetry, data calibration and interpretation, and novel algorithms developed for the new generation of interferometers. Synthesis instrumental polarisation calibration fundamentals for both linear (ALMA) and circular (JVLA) feed bases were reviewed, with special attention paid to practical problems affecting modern instruments.

A major theme of the meeting was the unique role of polarimetric observations in constraining the magnetic fields in regions of star formation at high mass — by Heshou Zhang, Katherine Pattle, Archana Soam and Thushara Pillai — and at low mass — by Anaelle Maury, Maud Galametz and Valeska Valdivia. Massive filaments are magnetised and the magnetic field may be as important as turbulence and gravity. Different methods for estimating the field strength (the Chandrasekhar-Fermi method and Zeeman splitting) are valid in different regimes and therefore difficult to cross-check. Polarimetric observations may potentially bring new insights into important micro-physics, such as the efficiency of grain alignment by magnetic fields, anisotropic radiation fields and molecular gas flows. Further studies would then enable more robust investigations of magnetohydrodynamic effects such as magnetic braking.

Polarimetry also complements total-intensity imaging of protoplanetary disks. From the fitting of ALMA polarimetric data from 0.87 to 3 mm in the archetypal disc around HL tau, Akimasa Kataoka infers that the grain sizes are much smaller than those derived from the total intensity spectrum alone, with important implications for planet formation.

Liz Humphreys and Helmut Wiesemeyer outlined how strong masers (SiO, H_2O and OH) are observed in cool evolved stars. The maser emission can display a high degree of circular and linear polarisation, revealing information about the magnetic field strength and morphology, which are dynamically important in the circumstellar envelopes, and which fall off with radius as expected for a toroidal geometry. Magnetic fields may also drive the shapes of the AGB stars to highly axisymmetric/aspherical planetary nebulae.

The meeting also covered extragalactic applications. The measurement of Faraday rotation at millimetre wavelengths in the cores of AGN is emerging as an important probe of the accretion rate, following early work on the Galactic Centre. Detections were presented for M87 and 3C273 by Keichi Asada and Talvikki Hovatta, and Hiroshi Nagai noted that the nondetection in Centaurus A may be a consequence of orientation.

An old problem, relevant to both AGN jets and star formation, is how to distinguish between vector-ordered and disordered but anisotropic field topologies, as both are capable of producing high degrees of polarisation. Carole Mundell considered both topologies in her discussion of AGN and gamma-ray burst sources. Monica Orienti pointed out that the degree of field ordering may also help to distinguish between particle acceleration mechanisms, for example in hot spots of radio galaxies.

Although the main theme of the workshop was interferometric imaging of polarisation, observations of the CMB with bolometric arrays were also discussed by Sean Bryan. There are well-known and exciting applications of CMB observations, including the potential detection of cosmological B-modes, but also a number of synergies, both observational (polarised point sources, foreground subtraction) and technical (improved lens materials for millimetre-wave receivers).

The meeting served a valuable purpose by identifying priorities for future developments in instrumentation. In rough order of importance, these were agreed to be:
- Very accurate circular polarisation calibration in continuum and line (Zeeman effect).
- Improved efficiency of polarisation calibration, avoiding the need for large parallactic angle rotation during an observation.
- Wider frequency coverage (for example, extending polarisation observations to the ALMA Bands 8–10).
- Lower systematics for measurement of linear polarisation, both to measure polarisation fractions < 0.1 % in protoplanetary discs and to achieve high dynamic range for total intensity.
- Polarisation calibration over the primary beam, for example using Mueller matrix methods. This is essential for ALMA polarisation mosaics.

All of the presentations are linked on the meeting website[1] and are available through the SAO/NASA Astrophysics Data System database.

Demographics

There were 62 registered participants at the workshop (Figure 1), three quarters of these coming from European institutions. One-third of all participants were women, and a similar fraction were early-career researchers, i.e., Masters and Doctoral students or junior postdoctoral scientists.

Acknowledgements

This event received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet] and from ESO. We are grateful to Elena Zuffanelli for her help with the meeting organisation.

Links

[1] QUESO Programme: https://www.eso.org/sci/meetings/2017/QUESO2017/program.html

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Report on the MOSAIC Science Colloquium

Spectroscopic Surveys with the ELT: A Gigantic Step into the Deep Universe

held at the Toledo Congress Centre, Toledo, Spain, 17–19 October 2017

Chris Evans[1]
Mathieu Puech[2]
François Hammer[2]
Jesús Gallego[3]
Ainhoa Sánchez[3]
Lucía García[3]
Jorge Iglesias[4]

[1] UK Astronomy Technology Centre, Royal Observatory Edinburgh, UK
[2] GEPI, Observatoire de Paris, France
[3] Universidad Complutense de Madrid, Spain
[4] Instituto de Astrofísica de Andalucía (CSIC), Spain

The Phase A design of MOSAIC, a powerful multi-object spectrograph intended for ESO's Extremely Large Telescope, concluded in late 2017. With the design complete, a three-day workshop was held last October in Toledo to discuss the breakthrough spectroscopic surveys that MOSAIC can deliver across a broad range of contemporary astronomy.

ESO's Extremely Large Telescope (ELT) will be the world's largest optical/infrared facility for at least a generation. It will have an immense collecting area, equivalent to gathering together all the current large telescopes in use today. Multi-object spectroscopy (MOS) will be a key capability of the ELT, able to harness its unprecedented sensitivity to deliver unrivalled surveys of the Universe. The MOSAIC design combines high-multiplex near-infrared and visible spectroscopy, together with adaptive optics (AO) spectroscopy in the near infrared that exploits the fantastic angular resolution of the ELT across a large field of view.

The workshop opened with the latest news on the ELT project from the ELT Programme Scientist, Michele Cirasuolo, and with overviews of the scientific motivations and technical design of MOSAIC, which were presented by François Hammer and Myriam Rodrigues. These were followed by talks that helped set the scene of the broader landscape in the

Figure 1. Workshop participants assembled in the Toledo Congress Centre.

mid-2020s, including Luca Pasquini presenting future developments at ESO's La Silla Paranal Observatory, Andrew Hopkins talking about the innovative TAIPAN survey underway on the UK Schmidt telescope and Suresh Sivanandam describing plans for an AO-fed MOS at the Gemini Observatory.

The ensuing science sessions spanned the diverse and wide-ranging topics that MOSAIC will address, namely the first galaxies and active galactic nuclei, galaxy evolution, the intergalactic medium, extragalactic stellar populations, and Galactic surveys. The sessions featured invited talks on the latest science results and relevant instrumentation developments. For example, Emma Curtis-Lake presented plans for Guaranteed Time Observations of high-redshift galaxies with the James Webb Space Telescope (JWST); Armando Gil de Paz provided tantalising glimpses of the first observations from the new Gran Telescopio Canarias (GTC) instrument, Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía (MEGARA); Olivier le Fèvre reflected on lessons learned from past high-redshift surveys and future aspirations with the JWST and ELT; Oscar Gonzalez talked about future surveys of the Milky Way bulge with the VLT third-generation instrument, Multi Object Optical and Near-infrared Spectrograph (MOONS) and MOSAIC; and finally there were results from the ESO Public Surveys carried out on the VLT MOS instrument VIMOS — Large Early Galaxy Astrophysics Census (LEGA-C) and VANDELS, which were presented by Arjen van der Wel and Laura Pentericci, respectively.

In addition to the contributed talks on recent results and ideas for MOSAIC surveys, the programme featured invited and contributed talks on detailed MOSAIC simulations using the Websim-Compass simulator (Puech et al., 2016), including: the first galaxies (Karen Disseau); galaxy rotation curves and dark matter (Jianling Wang); intergalactic medium tomography (Jure Japelj); high-redshift dwarf galaxies (Arjan Bik); and extragalactic massive stars (Oscar Ramírez-Agudelo).

Thinking about future ELT surveys, the final discussion focused on those that will be truly unique as they are not possible with other facilities. Participants converged on four key science cases which are potentially the most transformational and which will influence future decisions in instrument development. These are:
– First-light galaxies: Lyman-α emitters and physical properties;
– Inventory of matter: baryons and dark matter;
– Extragalactic stellar populations: evolved populations beyond the Local Group;
– Evolution of dwarf galaxies: formation, evolution and contribution to reionisation.

The meeting helped to demonstrate the high levels of enthusiasm and significant demand for MOS observations on the ELT. Ahead of the start of Phase B of instrument development, the advanced simulations presented in Toledo will be published, and new topics identified in the meeting will also be investigated in greater detail.

After the meeting, participants had an opportunity to visit the historic Marqués de Valdecilla library of the Universidad Complutense de Madrid (UCM) in Madrid, followed by an event presenting the MOSAIC concept to national media and senior officials of the Spanish Ministry and UCM.

Demographics

In total there were 75 participants (52:23 male:female), 20 invited presentations (14:6 male:female), and 17 contributed talks (11:6 male:female), with a good mix of senior and junior faculty and early-stage researchers.

Acknowledgements

The organisers would like to thank Red de Infraestructuras de Astronomía (RIA) in Spain and CNRS-INSU in France for financial support toward the meeting.

References

Puech, M. et al. 2016, Proc. SPIE, 9908, 9P

Links

[1] MOSAIC meeting webpage, including links to the presentations: https://www.mosaictoledo.org
[2] Further information and contact details are available at: http://www.mosaic-elt.eu
[3] The WEBSIM-COMPASS simulator for MOSAIC observations: http://websim-compass.obspm.fr

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Fellows at ESO

Darshan Kakkad

Darshan Kakkad

It's a pleasant summer night in Paranal; it just rained and we put the covers over the primary mirror at Unit Telescope 4 (also known as Yepun) for protection. The telescope domes are now closed and all of us are waiting until the weather improves. And here I am, sitting in the control room in the middle of the Atacama desert and, even more than the reader, I myself am wondering how the choices in my life got me here! None of my family members work in areas even remotely related to science. To them, I am the guy who looks through a small telescope in his backyard searching for aliens.

My story begins with a power cut in Delhi. It used to happen quite frequently on summer nights and the terrace in my house used to be the best place to get cool breezes. I was in middle school back then and, along with my siblings, we used to look at the stars and try to identify the constellations that we had learnt at school. Perhaps that was the first time I was interested in becoming an astronomer, although crediting Delhi power cuts does not seem the best "how I got inspired" story! I still remember when I got up early in the morning in 2005 and ran to the same terrace to see the sunrise — or rather, the eclipsed sunrise. It was probably the best eclipse I have seen in my life: the red Sun at the horizon covered by the Moon.

The seed was planted and all it required was some nourishment and a bit of luck. I was adamant about pursuing a career related to space and/or astronomy. After high school, I even went to a selection camp for the Indian Air Force in hopes of becoming a pilot (and, eventually, an astronaut: Teenage Dreams!). However, I was kicked out on the fifth day of selection. As nowhere in India offered an undergraduate degree in astronomy, I decided to settle for physics at the University of Delhi for my bachelor programme. During the first year of my undergraduate course, I got a Kishore Vaigyanik Protsahan Yojana (KVPY) fellowship from the Department of Science and Technology of India, which secured my education funding until the end of a masters degree. The fellowship continued as long as I did a research project in any institution in India each year during the summer. I visited the Giant Metrewave Radio Telescope (GMRT) facility as part of this fellowship to do a project on testing the new broadband feeds using pulsars. After a two-hour bus journey from the city of Pune through the lush, green landscape, I started spotting the antennas one after the other as we entered the observatory. Once there, my cellphone would be switched off for two full months, apart from during the occasional trips when I would go back into the city. Although my first observing run was a disaster, with no useful data acquired, the entire learning experience was something I enjoyed and I was sure of pursuing a PhD in Astronomy after that.

I was therefore excited to get an offer from ESO as part of the International Max Planck Research School (IMPRS) PhD school in Munich where I would change topics to work on active galactic nuclei (AGN) feedback with Vincenzo Mainieri and Paolo Padovani. The thought of working with data from one of the best telescopes in the world was fascinating and I could not wait to get started after my masters degree. Having limited experience with observational astronomy, I had a steep learning curve at the beginning of my PhD. There is a huge difference between doing a two-month internship and a PhD, where solving problems sometimes takes a year. Also, coming from a tropical environment, I wasn't familiar with the white thing they call "snow". So, climate-wise as well, it took me time to get used to the colder weather. Despite these differences, I enjoyed my work, especially the feeling of having solved a problem after some months.

Since my PhD, I have been heavily involved in integral field spectroscopy and sub-millimetre spectroscopy at both low and high redshifts. Using a multi-wavelength approach, I investigate whether the presence of ionised outflows in the host galaxies of X-ray selected AGN has an impact on the global properties of the host galaxy, such as the star formation rate, molecular gas mass or gas densities. I have been using data from the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) at the VLT, the Wide-Field Spectrograph (WiFeS) at the Australian National University (ANU) and the Atacama Large Millimeter/submillimeter Array (ALMA) for this purpose, collaborating with people at ESO, the ANU, the Istituto Nazionale di Astrofisica (INAF) in Italy and various institutions in Japan and the UK. As an ESO fellow, I am continuing to work in this field with more diverse and deeper data sets.

Working with data is amazing in itself, but as a person who aspires to be an astronomer, I felt it was important to have the experience of working in the place where the real action happens — the Observatory itself. I was keen to see how instruments work and experience the challenges that can occur when taking observations. This is what motivated me to join ESO for a fellowship in Chile and, indeed, the experience at the Paranal Observatory is completely different compared to sitting in a chair and looking at the data. It's just amazing how dedicated people at the Observatory are to solving issues each day in order to have the telescope ready for the observations every night.

And that's what we are doing right now! It's almost 2am. The rain has stopped and the weather officer has given the clearance to open the domes. The telescope operators have put on their helmets to go to the Unit Telescopes and start the opening sequences and within a few minutes we will start observing again. We're all happy to have managed even three hours of observation over the night. People say, "Time is Money". Well over here, "Time is Science!"

Elizabeth Bartlett

Elizabeth Bartlett

In 1995, when I was seven or eight years old, my mum picked up a book called Skywatch for a couple of pounds in a local supermarket. The book had a page of information on each planet, as well as galaxies and different types of stars, along with some pictures and artists' impressions of celestial objects. I often wonder what would have happened if my mum had walked past that book or had picked up something different instead; that book set me on a journey that has taken me around the world and currently has me sitting in Santiago (Chile) after a shift at ESO's Very Large Telescope.

If that book dug the foundations for my future career, then the concrete was set by seeing comet Hale Bopp just a couple of years later through my grandfather's small refracting telescope (usually used for watching passing ships). Eager to fuel this obsession of mine, my grandfather bought me every single astronomy book he found in a charity shop or car boot sale, right up until the day he died. This led to an eclectic personal library, ranging from that first "Skywatch" book, right up to an advanced level textbook about planetary atmospheres, which was way beyond my understanding at 12 years old!

My passion for astronomy remained with me throughout school, but I had no idea that astronomy could be an actual career path until I went to university. I studied Physics and Astronomy at the University of Southampton as, unlike any other institution at the time, the course included the opportunity to visit and take data at a "real" observatory, the Observatorio del Teide in Tenerife, home of the Instituto de Astrofísica de Canarias 80-centimetre (IAC-80) telescope. I remember arriving at the observatory after dark, getting off the bus and really seeing the night sky for the first time — that's when I knew I wanted to be an astronomer. The module was about more than just inspiring us; we learnt about right ascension, declination and hour angles, how to plan an observing run, CCDs, data calibration, and most crucially, how to get along with everyone at 2400 m in a snowstorm! While my other astronomy modules taught me the physics behind the greatest astronomical discoveries, this module taught me *how* these discoveries came about, from data to the resultant paper.

I spent the final year of my degree programme at the Harvard-Smithsonian Center for Astrophysics (CfA) in Boston. Here, I did the research for my Masters thesis in the High Energy Astrophysics Division with Michael Garcia, attempting to do proof-of-concept for X-ray timing techniques with data from the X-ray Multi-Mirror satellite (XMM-Newton) ahead of the, now cancelled, International X-ray Observatory. Working at the CfA gave me a taste for the more day-to-day aspects of life as an astronomer, and working with high-energy space-based data brought a completely different set of challenges.

I returned to Southampton for my PhD, to work with Malcolm Coe as part of the X-ray binary group, monitoring the Magellanic Cloud population. My research focused on multi-wavelength studies of these sources, both individually and as a population. I used simultaneous X-ray spectral and timing analysis to constrain system geometries, and worked on identifying new high-mass X-ray binary candidates by cross-correlating searches of X-ray sources with optical, radio and infra-red catalogues, and developing techniques that make use of multi-wavelength data to discriminate between different types of sources. This multi-wavelength project was particularly appealing as it allowed me to combine my newly gained skills and knowledge in X-ray astronomy with my passion for the night sky. My supervisor promised me several observing trips, and he delivered, with yearly visits to the South African Astronomical Observatory (SAAO) to use the 74-inch Radcliffe telescope and a trip to ESO's La Silla observatory to use the New Technology Telescope.

After my PhD I moved to South Africa to take up a Claude-Leon research fellowship at the University of Cape Town. I expanded my work to cover other X-ray emitting massive binaries, such as colliding wind binaries, and became heavily involved with the Southern African Large Telescope (SALT) — technically the biggest single telescope in the Southern Hemisphere. I established a dedicated campaign to monitor the X-ray bright supergiant emission-line sgB[e] stars in the Magellanic clouds, and was also involved in the testing and development of the SALT data pipeline and PySALT python-based software package. SALT shares the SAAO site with smaller telescopes, so while observing on the 74-inch telescope I would often run over to SALT after starting an observation, not just to use their coffee machine, but also to see operations. SALT is only operated in service mode and closely follows the ESO model (as it is mostly run by ex-ESO fellows, such as, Petri Vaisanen and Eric Depagne). Getting to see my own data being taken was a treat that few astronomers get to experience. I have no doubt that it was the combination of working closely with SALT and working with the older, more hands on, telescopes that made my application attractive to ESO.

My time in South Africa really opened my eyes to the power of astronomy for social change. Observatories are built in remote locations and in developing countries; this often means near disadvantaged communities. To build an observatory you need infrastructure, such as paved roads, electricity, water and the Internet. To maintain an observatory, you need trained engineers on hand who can fix the telescopes and instruments, and staff to take care of the food and lodging for the astronomers. World-class telescopes, such as the VLT, generate interest that leads to tourism providing a huge boost to local economies. Observatories can provide employment across many sectors in regions where there may be few opportunities. One could argue that a telescope's success should not just be measured in the number of papers it produces but on how it enriches the communities that surround it.

Now an ESO fellow, I am part of the science operations team at Paranal Observatory. I spend 80 nights a year observing at Kueyen (Unit Telescope 2 [UT2]), the home of the UV-Visual Echelle Spectrograph (UVES), the wideband ultraviolet-infrared spectrograph X-shooter and the Fibre Large Array Multi Element Spectrograph (FLAMES). While there are many observatories around the world that allow one to gain observing experience, I have the chance to go beyond this by working at ESO's Paranal Observatory and to be part of something truly bigger than me or my work.

Last year I was involved in interventions on all three of the instruments on UT2, including recovering the resolution of the blue arm of UVES and the recommissioning of X-shooter after it was dismounted and dismantled to repair the atmospheric dispersion correctors. I am currently the instrument scientist for FLAMES and enjoy having the opportunity to leave a mark on Paranal beyond my time here — or at least until FLAMES gets decommissioned! I was also fortunate enough to be at Paranal just after the initial detection of the gravitational wave GW170817. Being at the observatory at such a time was an absolute privilege (whilst simultaneously being incredibly stressful!) and the atmosphere in the control room during those nights will stay with me for a long time.

The start of Period 101 coincides with the beginning of my final year of duties at Paranal. I have been awarded 20 hours of X-shooter time to look at my targets in this period and my hope is that I get the chance to execute some of my own observations. That would be a very special moment for me as my time at Paranal draws to a close and would complete my experience as an ESO fellow.

Hau-Yu Lu

I grew up on a very tropical island in East Asia, Taiwan. I studied at the National Taiwan University, where I majored in physics. One of the focuses of the physics department is on particle physics and several professors in the theoretical group were quite stimulating. I particularly enjoyed brainstorming sessions on mathematical physics and used to follow the related group meetings and seminars. In particular, I was very impressed by the culture in the group under Pei-Ming Ho. Thanks to that team I have an attitude of constantly questioning myself until I converge on a position that feels self-consistent and logical. I also became an efficient and motivated self-learner and greatly enjoyed my college life.

I quickly realised that I could understand theoretical and fundamental physics, which I greatly appreciated, but found it difficult to be creative when doing research in these areas. I was capable of working on phenomenological theories based on fundamental physics, on the other hand, but found that the models of dark matter and dark energy were only loosely constrained by experiments. I started thinking about starting again as an observer, although I did not have a concrete idea about what to do. I had a

Hau-Yu Lu

rough idea to use the spatial distributions and motions of galaxies in a cluster to probe the gravitational potential of the dark matter, so surveying galaxy groups or clusters might be a good place to start.

Following up on this simple idea, I joined the group under Tzi-Hong Chiueh in Taiwan University and was introduced to Lihwai Lin and Bau-Ching Hsieh, postdoctoral researchers at the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA). At that point, very massive galaxy clusters could be identified by either X-ray observations, the Sunyaev-Zel'dovich effect, strong lensing, or the photometric red sequence. However, the identification of smaller groups and clusters was ambiguous, largely because of the poor detection limits in relatively shallow photometric surveys as well as the poor completeness of redshift samples. We therefore looked into how to associate sparsely sampled galaxies in the redshift domain using an artificial neural network, and benchmarked our algorithms based on mock galaxy surveys generated from *N*-body simulations.

When reading papers about how *N*-body simulations were made, I started to realise that mock galaxy surveys were too artificial for my purposes. First, there is the artificial criterion that dark matter overdensities can be regarded as galaxy-forming dark halos. Then, galaxies were assigned to individual dark halos based on the halo occupation distribution function, which is rather empirical. Finally, galaxies were assumed to have certain luminosities based on yet another empirically assumed mass-to-light distribution function. This same mass-to-light distribution function plays a critical role in allowing us to relate observations to the underlying actual structures. In other words, our conclusions based on observations can be hugely biased if we do not understand this function.

Mass and light are linked by the baryon fraction as well as the "laws" governing how high-mass stars form out of baryons. Star formation laws exist, but are not yet understood from first principles. Not even close! In fact, even just forming a luminous OB cluster is a highly non-trivial phenomenological problem. This is because the radiative feedback from the highest mass stars may destroy the parent molecular cloud as soon as they form. I therefore decided that my PhD thesis topic was to understand how OB stars accrete, and what is the specific parent molecular cloud morphology that would permit the subsequent formation of lower mass stars.

My thesis supervisor was Paul Ho at ASIAA who was leading the SubMillimeter Array (SMA) project, which was the most powerful tool that could be used to spatially resolve detailed molecular cloud structures at that time. For the last three years of my PhD, I went on an exchange to the Harvard-Smithsonian Center for Astrophysics (CfA), to work with Qizhou Zhang. During these years, I had the opportunity to engage more with the SMA community and visited the National Radio Astronomy Observatory in Socorro for several months during the upgrade of the NRAO Karl G. Jansky Very Large Array (JVLA). I would specifically like to thank Melvyn Wright at Berkeley, who is still teaching me about radio interferometry (and writing in English).

After my PhD, I returned to ASIAA as a postdoctoral fellow, and that period also served to substitute for my military service. My research area was significantly broadened during that time and I got my first masters students, Yuxin Lin and I-Hsiu Li — of whom I am extremely proud — to join my journey to investigate how amorphous low-density gas clouds evolve to become OB cluster-forming clouds, and to learn where and when dust grains grow in a protoplanetary disc. However, they were apparently too good as they ended up being recruited to join other researchers' journeys, which I am also very glad about, of course.

These same years also coincided with the start of science operations for the Atacama Large Millimeter/submillimeter Array (ALMA). As ASIAA is a partner institution, I had the opportunity to experience ALMA operations first-hand. All of these experiences formed me and paved the way to my joining ESO as a postdoctoral fellow in Garching, as well as turning me into who I am now. I have also contributed to the report on the QUESO 2017 workshop (p. 46) in this issue of the ESO Messenger, which you might find of interest!

Personnel Movements

Arrivals (1 January–31 March 2018)

Europe

Bezawada, Nagaraja Naidu (UK)	Detector Engineer
Brandt, Daniel (DE)	IT Specialist Database Administrator
Dominguez-Faus, Lidia (ES)	Software Engineer
Gnatz, Amelie (DE)	Documentation Specialist
Hucke, Jannett (DE)	Internal Auditor
Jaillot, Caroline (FR)	Electronic Engineer
Pathak, Prashant (IN)	Fellow
Prole, Daniel (UK)	Student
Sanchis Melchor, Enrique (ES)	Student
Serra, Benoît (FR)	Fellow
Tax, Tomas (CZ)	Student
Vieser, Wolfgang (DE)	ESO Supernova Education Coordinator
Wallace, Mark (AU)	Control Engineer
Zanoni, Carlo (IT)	Opto-Mechanical Engineer

Chile

Bian, Fuyan (CN)	Operation Staff Astronomer
Courtney-Barrer, Benjamin (AU)	Telescope Instruments Operator
Figueira, Pedro (PT)	Operation Staff Astronomer
Leclercq, Julien (FR)	Mechanical Engineer
Parra, Ricardo (CL)	Optical Coating Engineer

Departures (1 January–31 March 2018)

Europe

Allaert, Eric (BE)	Senior Software Engineer
Ghiretti, Paolo (IT)	Civil Engineer
Gonzalez Fernandez, Ariadna Irene (ES)	Student
Zivkov, Viktor (DE)	Student

Chile

Cox, Pierre (FR)	Senior Scientist
Jaffe Ribbi, Yara Lorena (VE)	Fellow
Johnston, Evelyn (UK)	Fellow
Neumann, Justus (DE)	Student
Slusarenko, Nicolas (CL)	Software Engineer

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ESO, the European Southern Observatory, is the foremost intergovernmental astronomy organisation in Europe. It is supported by 16 countries: Austria, Belgium, Brazil, the Czech Republic, Denmark, France, Finland, Germany, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland and the United Kingdom. ESO's programme is focused on the design, construction and operation of powerful ground-based observing facilities. ESO operates three observatories in Chile: at La Silla, at Paranal, site of the Very Large Telescope, and at Llano de Chajnantor. ESO is the European partner in the Atacama Large Millimeter/submillimeter Array (ALMA). Currently ESO is engaged in the construction of the Extremely Large Telescope.

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Contents

Front cover: ALMA observes gaps in the young protoplanetary disc AS 209 in the Ophiuchus star forming region. The outer gap is consistent with a giant planet and the inner gap may indicate a smaller planet closer to the central star.
Credit: ALMA (ESO/NAOJ/NRAO)/D. Fedele et al.