The Messenger

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Astronomy in Ireland
ELT – Where the Secondary Mirror Becomes a Giant
KLASS – The Role of Low-Mass Galaxies from Cosmic Dawn to Cosmic Noon
ESO Science Ambassadors

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Front cover: The Milky Way stretches over one of the Auxiliary Telescopes of the VLTI. Credit: Y. Beletsky/ESO

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Astronomy in Ireland

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Astronomy has been very important in Ireland since ancient times. In the Victorian era, the country had not only the largest reflector in the world, but also the largest refractor. Modern astronomical research is concentrated in various Irish universities as well as the Dublin Institute for Advanced Studies. Astronomy is very popular among the public at large, and also as a means of promoting graduate uptake in Science, Technology, Engineering and Mathematics (STEM). After providing some historical background, we give a broad-brush review of astronomical research in the country with the intention of encouraging collaboration with Ireland, the newest member of the ESO family.

Ken Williams

Figure 1. The so-called Sundial Stone decorates one of the mounds at Knowth in the Boyne Valley and dates back 5000 years. Interpreting such art is notoriously difficult but there is little doubt that nearby Newgrange was deliberately aligned with sunrise on the winter solstice.

Interest in astronomy in Ireland can be traced back over 5000 years. The pre-Celtic inhabitants built magnificent structures such as those in the Boyne Valley northwest of Dublin long before the pyramids — and even Stonehenge — were constructed. One in particular, at Newgrange, is renowned for marking the winter solstice sunrise. For a few days either side of the shortest day of the year, light from the rising Sun shines through the roofbox above its entrance, traverses a 20–metre long passage, and illuminates the main chamber inside the giant mound. The precision achieved is remarkable when one considers that the alignment is perfect for when the monument was built 5200 years ago. The tilt of the Earth at that time was 24 degrees as opposed to its current 23.5 degrees. To witness the phenomenon now, one has to wait roughly 10 minutes after sunrise for the light to shine into the chamber, whereas then it would have been visible directly at sunrise. Moreover, back when it was built, sunlight would have penetrated to just touch the back wall of the monument; the Neolithic people who constructed Newgrange had solved a 3D astronomical puzzle.

Peter Gallagher, DIAS

Figure 2. Historic Birr Castle is not only the site of what was the largest telescope in the world for many years, the Leviathan, but also the location of Ireland's LOFAR station (I-LOFAR) which operates as part of the international LOFAR facility. I-LOFAR is managed by a consortium of Irish research institutes led by TCD and DIAS.

In more modern times, Ireland was, for a brief period during the Victorian era, home to not only the largest reflector in the world, the so-called Leviathan at Birr Castle in County Offaly, but also the largest refractor at Markree Castle, County Sligo. The Leviathan, with its six-foot (1.83-metre) mirror, is no doubt the better known instrument — Lord Rosse used it to discover and subsequently name such famous objects as the Crab and Whirlpool nebulae. This interest in astronomy in Ireland during the 19th century also gave rise to a major industry: telescope making. Founded in Dublin by Thomas Grubb, and subsequently managed by his son Howard, the firm of Grubb manufactured some of the largest telescopes in the world, such as the Great Refractor of the Vienna Observatory and the Great Melbourne Telescope. Howard Grubb also made eclipse instruments which proved crucial in testing Einstein's general theory of relativity, 100 years ago.

Ireland is also the place where the first photoelectric experiments were performed by Stephen Mitchell Dixon and William Stanley Henry Monck. At Monck's observatory in the centre of Dublin, the relative brightness of Venus and Jupiter was recorded in 1892 using a simple photoelectric cell made by George Minchin. This was followed a few years later by the earliest such measurements of stars at William Wilson's observatory in County Westmeath, not far from Dublin.

The two oldest purpose-built observatories in Ireland are located in Dunsink, close to the centre of Dublin, and its sister establishment in Armagh. Dunsink, which was founded as part of Trinity College Dublin in 1785, was home to Ireland's most famous mathematician, William Rowan Hamilton. Work at the observatory centred on using stars to measure time but it was also the site of some of the earliest attempts at determining stellar parallaxes.

The modern astronomical era in Ireland can be said to have begun in 1947 with the acquisition by the Irish State of Dunsink Observatory as part of the fledgling Dublin Institute for Advanced Studies — at that time headed by the well-known physicist Erwin Schrödinger. The importance of accessibility to remote sites to carry out serious astronomical research was glaringly obvious. As a result of an initiative from Eric Lindsay, then Director of Armagh, Ireland initially had access to astronomical facilities at Bloemfontein (South Africa) through an international treaty involving Armagh, Dunsink and Harvard (USA). Eventually this was replaced by the use of the telescopes at the La Palma Observatory (Spain) under an agreement between the Irish National Board of Science and Technology and the then Particle Physics and Astronomy Research Council in the UK.

Today, Physics with Astronomy is offered as a degree course at several Irish universities. High-tech industry is a very important component of the modern Irish economy and the role of astronomy in promoting STEM (science, technology, engineering and maths) as a career choice is increasingly acknowledged.

Ireland was a founding member of the European Space Agency and this has led to its involvement in many well-known science missions, such as the ESA INTERnational Gamma-Ray Astrophysics

Antonio Martin-Carrillo

Figure 3. Undergraduate students from UCD undertake an astronomy observing field trip to a professional observatory in their final year.

Laboratory (INTEGRAL) and the Herschel Space Observatory, as well as a number planned for the future like Solar Orbiter and the James Webb Space Telescope. Ireland is looking forward to participating fully in ESO as its newest Member State. Public engagement in astronomy is certainly very strong in the country, with one of the highest *per capita* memberships of amateur astronomical societies in Europe. Here we provide just a flavour of the main astronomical interests in our research establishments as a basis for possible collaboration with other members of the ESO community.

- The Dublin Institute for Advanced Studies (DIAS) primarily conducts research into star formation and solar physics although it also retains an interest in high energy astrophysics. As an example, it manages the country's involvement in the High Energy Stereoscopic System (HESS) based in Namibia as a facility for gamma-ray astronomy. In the past few years DIAS has created a new astronomical detector group concentrating on optical/near-infrared Microwave Kinetic Inductance Detectors (MKIDs). Before joining ESO, the institute was already a partner in a number of astronomical projects in Chile, such as GRAVITY on the Very Large Telescope Interferometer (VLTI). DIAS is playing a leading role in the Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope (JWST) and on the ARIEL Space Mission, which will explore exoplanet atmospheres.

- Trinity College Dublin (TCD) is Ireland's oldest university and has a vibrant astrophysics research programme covering theoretical and observational aspects of exoplanets, low-mass and massive stars, supernovae, electromagnetic counterparts of gravitational wave events, and light pollution studies. TCD Astrophysics has five faculty members who have leading roles in international consortia for the JWST and Colorado Ultraviolet Transit Experiment (CUTE) space missions (the latter being an ultraviolet spectroscopy mission to study exoplanet atmospheres), as well as a number of large ESO-related projects such as the NTT transient follow-up programme (e)PESSTO, the VLT gravitational wave follow-up programme ENGRAVE, and the 4-metre Multi-Object Spectroscopic Telescope (4MOST), a future spectroscopic survey instrument for VISTA. TCD builds on a strong Irish heritage in astronomy. The current TCD Astrophysics group runs undergraduate and postgraduate programmes in physics and astrophysics, with about 20 students graduating per year and growing numbers of postgraduate opportunities. It is anticipated that the existing use of ESO facilities will expand further in the next few years and bolster research opportunities.

- Dublin City University (DCU) is one of the country's newest universities, and consistently features as one of the top young universities worldwide. About 15 students graduate every year from its Physics & Astronomy degree programme. DCU hosts the Centre for Astrophysics & Relativity[1] (CfAR), comprising eight faculty members drawn from the School of Physical Sciences and the School of Mathematical Sciences. There are particular research strengths in observational astronomy, computational astrophysics and general relativity. Current research topics range from exoplanets and weakly ionised astrophysical plasmas to high energy astrophysics, supermassive black holes, gravitational waves and mathematical relativity. Before Ireland joined ESO, DCU collaborated extensively in the use of its facilities and anticipates that such collaborations will increase in the coming years.

- University College Dublin (UCD) has a distinguished tradition in astrophysics, starting from pioneering work in the 1960s on the development of ground-based high-energy gamma-ray astronomy. Astrophysics continues to

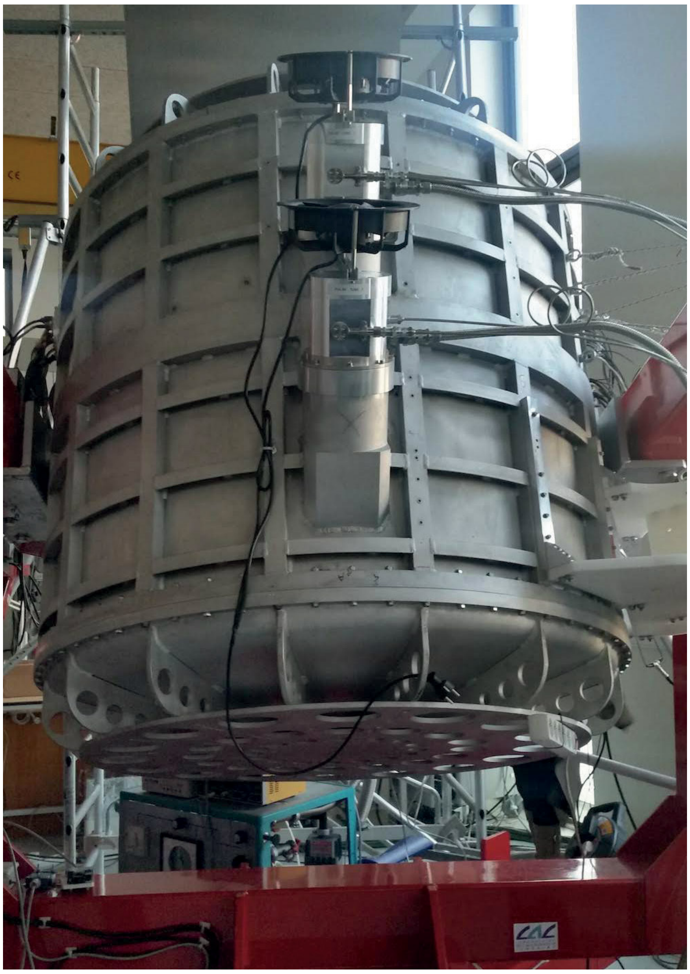
C. O'Sullivan, Maynooth University

Figure 4. The ground-based cosmic microwave background (CMB) instrument called the Q&U Bolometric Interferometer for Cosmology (QUBIC) being integrated in Paris before being shipped to its observing site in Argentina. The QUBIC optics were designed by the Maynooth team.

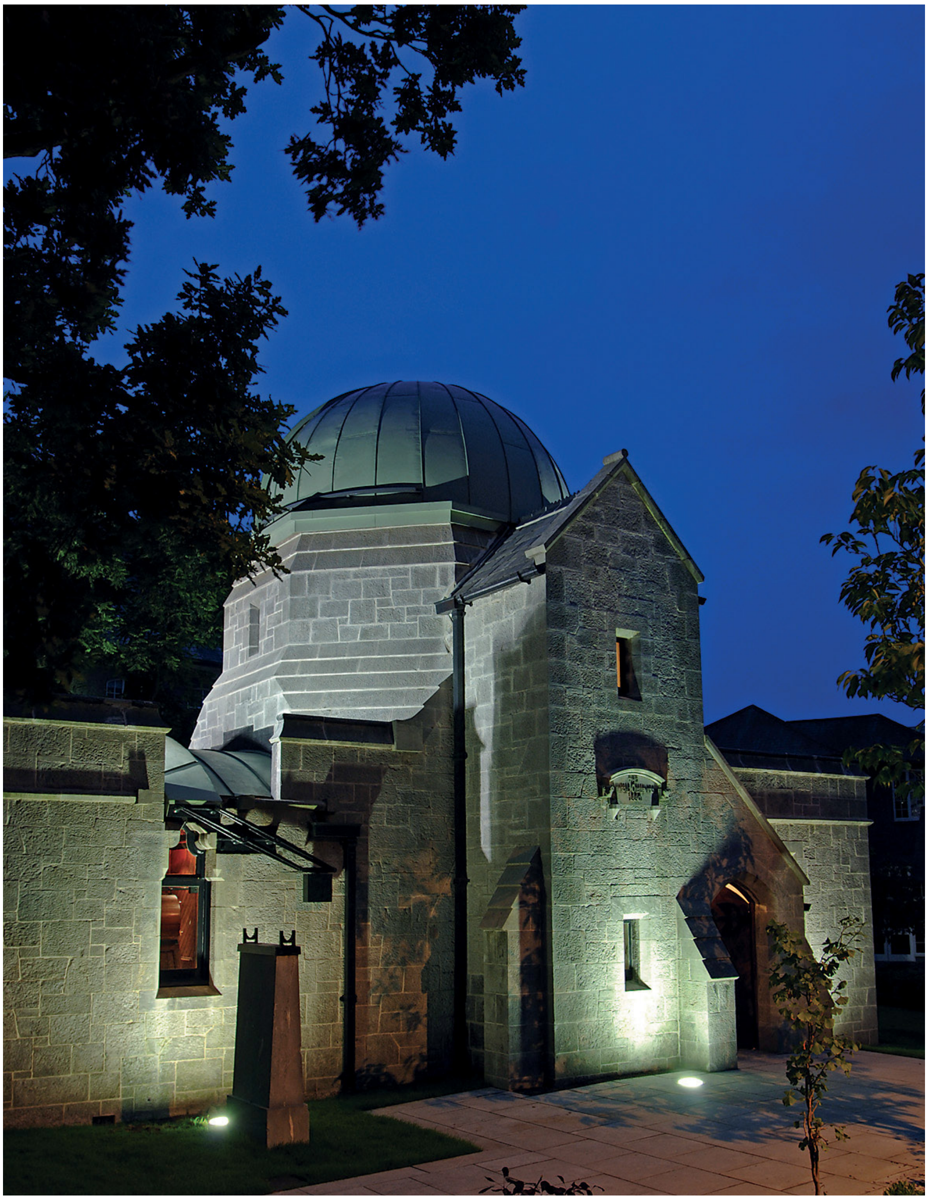

Figure 5. Crawford Observatory, University College Cork.

be a vibrant research area, with about 20 staff, researchers and postgraduate students. UCD astronomers are leading research on a wide range of topics, including the search for and characterisation of galactic and extragalactic very high-energy gamma-ray sources with the VERITAS telescope array, the Cherenkov Telescope Array (CTA), astrophysical jets with the LOw-Frequency-Array (LOFAR), pulsar timing, shock acceleration theory, gamma-ray bursts and other transients detected by NASA's Swift and Fermi missions and ESA's INTEGRAL and XMM-Newton satellites, progenitors of supernovae and tidal disruption events, terrestrial gamma-ray flashes, development of novel scintillators and gamma-ray detectors, CubeSats, robotic telescopes, electromagnetic counterparts to gravitational wave sources, data mining astrophysical transients, star and planet formation research with the Hubble Space Telescope, the future ARIEL space mission to characterise exoplanet atmospheres, ESO's VLT and VLTI telescope facilities, the Gemini telescopes and ALMA. Development of the Educational Irish Research Satellite (EIRSAT-1) — Ireland's first satellite — is being led by UCD astrophysics students and staff. The mission will fly innovative Irish technology in space, including a new detector to observe gamma-ray bursts. Annually, 12–15 BSc students graduate from the Physics with Astronomy & Space Science programme, and about the same number of MSc students graduate from the Space Science & Technology programme.

- **Maynooth University (MU)** offers an undergraduate degree in Physics with Astrophysics and postgraduate research degrees in Astrophysics at Masters and PhD level. Research is carried out by two groups in the Department of Experimental Physics. The Space Terahertz Optics group has internationally-recognised expertise in millimetre-wave optics, electromagnetic instrument qualification and astronomical observation. They have been core team members of a number of important astronomical projects including ALMA, the High Frequency Instrument (HFI) on the ESA Planck Surveyor and the Heterodyne Instrument for the Far-Infrared (HIFI) on the Herschel Space Observatory. The star and planet formation group has expertise in high angular resolution and spectroscopic observations of outflow and accretion activity in young stars and brown dwarfs. The group is involved in several international collaborations and primarily works in the optical and near-infrared regimes using ESO facilities.

- **The National University of Ireland Galway (NUI Galway)** was established in 1845 and is the leading higher education and research organisation in the west of Ireland. The Centre for Astronomy (CfA) hosts one the largest collection of astrophysics researchers in Ireland, and members of the centre carry out research in astronomy, astronomical instrumentation and computational astrophysics. Research topics include applied imaging, adaptive optics, clusters and exoplanets, gamma-ray astronomy, high speed Stokes polarimetry, pulsars, star formation and astrochemistry, ultra-cool stars, and astro-informatics. CfA astronomical instrumentation researchers designed and built the Galway Astronomical Stokes Polarimeter (GASP), which has had two recent runs on the ESO 3.6-metre telescope at La Silla. Another visitor instrument built here was the Galway High Speed Photometer (GUFI) at the Mount Graham Observatories. NUI Galway also houses the Irish Centre for High-End Computing (ICHEC) which is extensively used by Irish astrophysicists carrying out numerical simulations. A new MSc programme, Astronomical Instrumentation and Technology, had an intake of six students in 2018 and is steadily growing.

- University College Cork (UCC) can trace its heritage in astronomical research back to 1880, with the construction of the Crawford Observatory (which included instruments made by Howard Grubb, mentioned above) on the university campus (see Figure 5). Astrophysics research in UCC is focused on three core themes, involving: (i) multi-wavelength observations of cataclysmic variable and X-ray binaries; (ii) Very Long Baseline Interferometry (VLBI) and polarisation studies of active galactic nuclei; and (iii) theoretical high-energy astrophysics (including relativistic plasma astrophysics and radiative transfer problems as applied to gamma-ray bursts). The group is involved in ESA's Athena X-ray mission and the proposed Theseus M5 mission.

- Cork Institute of Technology (CIT) operates the Blackrock Castle Observatory[2] (BCO) which houses an internationally award-winning science centre focusing on astronomy and space science; this was opened to the public in 2007. The objective of the BCO is to use astronomy and space science to enthuse visitors, young and old, about the benefits of science and critical thinking. More recently, the observatory has acted as an advocate for Ireland's involvement in space. BCO welcomes around 105 000 visitors annually, with an additional 10 000 pre-university students engaged in formal and informal workshops. The observatory also operates as the ESO Science Outreach Network point of contact for Ireland. Research at BCO concentrates on small robotic observatories and high-speed photometry, which aims to minimise the negative effects of atmospheric turbulence on photometric measurements.

Finally, it should be mentioned that the professional organisation for Irish astronomy is the Astronomical Sciences Group of Ireland (ASGI), which was founded in 1974. It is a cross-border organisation with members in both Ireland and Northern Ireland, and is affiliated to the European Astronomical Society. The ASGI hosts the annual Irish National Astronomy Meeting each September, which attracts up to around 100 delegates, with a particular emphasis on encouraging talks from postgraduate researchers.

Links

[1] Centre for Astrophysics & Relativity (CfAR): www.cfar.ie
[2] Blackrock Castle Observatory: www.bco.ie


Dan O'Regan

Figure 6. Blackrock Observatory in County Cork. This is largely used as an outreach facility to promote astronomy to a broad audience.

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The ESO Users Committee: Giving Users a Voice

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The Users Committee (UC) was introduced at ESO in 1978 and since its first meeting in September of that year it has assisted the Director General and the ESO management in improving the performance of the Organisation, including scientific access, operations and data management facilities, and other services related to the scientific products. The UC is an advisory body that represents European users of both La Silla Paranal observatory, including the Atacama Pathfinder EXperiment (APEX), and the Atacama Large Millimeter/submillimeter Array (ALMA). It is the main channel of communication between the users and ESO. UC members' engagement with specific activities has evolved over time in line with the development of ESO's facilities and the expansion of the ESO community. This article provides information on the composition of the UC and details of its main activities, and highlights topics that have been discussed over the last decade.

Who are we?

The current members of the UC are listed in Table 1, alongside country of representation, host institute and role. Figure 1 shows the UC at its 43rd meeting. The UC represents all ESO users with one representative from each ESO member state, one from Chile for matters related to La Silla Paranal and ALMA, and one from Australia who according to the partnership agreement refers only to matters relating to La Silla Paranal. Users from other countries are welcome to approach the UC chair and co-chair on relevant aspects at any time. UC members are selected by the Director General from three suitable candidates proposed by national authorities (ESO council members and the national Chilean ESO Committee).

The UC is the youngest ESO committee according to the average age of its members. It is also the committee with the best gender balance, with over 50% female members. It has required many years of supportive activity to reach this level of diversity while ensuring no compromise in the research knowledge and expertise represented within this committee. An important aspect of UC members is their hands-on experience with ESO programmes — from their frequent use of ESO telescopes and instrument facilities, to the services and tools that ESO makes available to the community with the goal of advancing scientific discoveries. Their experience encompasses the use of tools to prepare, obtain and reduce ESO data, the submission of data products to the ESO archive, and the production of written contributions, for example to the Messenger, as well as the advertising of scientific results via the ESO press. Furthermore, the research fields of UC members encompass a broad range of scientific topics which closely match those that can be addressed with ESO facilities.

Figure 1. Users Committee members visited ESO headquarters in April for the 2019 spring meeting.

What do we do?

The UC serves as an interface between the ESO users and ESO representatives (for example, the Director General and the heads of different departments) to provide users with an understanding of how ESO facilities are used, how services and support are perceived, and to obtain explanations of what, why and how ESO does what it does (see the UC Rules of Procedure[1]). In practice, the UC collects and distributes information, and advises, discusses and provides recommendations on matters directly related to the users' experience with ESO facilities at different stages – from the acquisition and processing of observational data to the distribution of data products. More details about past matters pertaining to the UC can be found in Wisotzki (2001) and van Loon (2009); here we focus on current issues.

The UC formulates recommendations aimed at improving the users' experience with ESO facilities. These recommendations result from consolidated feedback obtained from users, consultation among UC members and between the UC and ESO representatives. The UC collects feedback from users primarily via an annual poll, presenting the users with a set of questions that probe their experience with ESO facilities. Past experience suggests that users seldom approach UC members directly if not prompted to do so, and even then it is difficult to obtain a large number of responses (only 500 in 2018). On the other hand, if UC members proactively advertise their UC role to colleagues and at events where astronomers are reachable, such as conferences and workshops, the amount of feedback increases. At a time when users receive regular questionnaires about aspects of their work it can be hard to engage with yet another poll. However, the statistical information gleaned from the UC poll is tremendously important in supporting discussions with ESO representatives and acquiring a sound view of general aspects that are common to many users. A brilliant idea may come from a single individual, but its implementation requires a much larger effort involving many more people.

The UC meets ESO representatives once a year in spring, usually following a meeting of the Scientific Technical Committee (STC). At this meeting, updates on ESO activities are presented and discussed, including the following: statistical information on the use of ESO telescopes with updates on major happenings that have influenced operations over the past year; updates on the development of new instruments and their timescales; progress reports on long-term activities (such as the production and implementation of a new observing tool); and work towards software analysing the data (quality assessment and data reduction tools).

In addition, each year a special topic is addressed, with tailored questions included in the UC poll and invited presentations by a few experienced users at the UC meeting. A list of the special topics addressed over the past decade is given in Table 2. A report describing the results of the UC poll and the minutes of meetings between the UC and ESO representatives are publicly available on the respective UC meetings webpages[2]. Following the spring meeting, the UC formulates a list of recommendations that, once agreed with ESO representatives, are distributed to the users directly by the UC members, and are posted on the website indicated above. Progress on these recommendations is discussed at a mid-term teleconference involving UC members and key ESO staff. While some recommendations may be resolved within six months to a year, others may have a wider impact on ESO operations and the community and require a long-term investment of resources (for example, it took many years to gradually remove the platform dependence for ESO tools).

Highlights of UC recommendations and their current status

Observations

A long-standing item that has figured in most UC reports is the need to improve the process by which observing proposals (Phase 1) are prepared and evaluated. For some time ESO has been developing a new tool which is embedded in a complex structure linked to other parts of the observing process (for example, to the exposure time calculator). The UC has monitored the criticisms from users and has often discussed them with ESO representatives to make sure that they are considered in the construction of the new tool. A demo of this tool was first shown at the UC meeting in 2018 while a new web-based tool for the preparation of the observations (Phase 2) was recently released. The latter reflects the feedback from the users who successfully obtained observing time; first impressions were extremely positive.

Pipelines

Major steps have been taken to develop and improve data reduction tools at ESO. Initially pipelines did not exist, then they were not good enough, now they have improved and the focus has shifted toward improving the documentation (including video tutorials and cookbooks explaining the essential steps), bug reports, sharing algorithms and implementing advanced reduction steps. This is a gradual process that begins again each time a new instrument is

Table 1. Members of the Users Committee in 2019.

Country	Member, Institute
Austria	Wolfgang Kausch, University of Innsbruck
Belgium	Arjen van der Wel, Ghent University
Czech Republic	Michaela Kraus, Czech Academy of Sciences
Denmark	Lisa Bech Christensen, University of Copenhagen
Finland	Rubina Kotak, University of Turku
France	Nicolas Bouché, IRAP
Germany	Maria-Rosa Cioni, Leibniz Institute for Astrophysics Potsdam
Ireland	Rebeca Garcia López, Dublin Institute for Advanced Studies
Italy	Maria Teresa Beitran, INAF – Observatory of Arcetri
The Netherlands	Karina Caputi (Chair), Kapteyn Astronomical Institute
Poland	Łukasz Wyrzykowski, Obserwatorium Astronomiczne UW
Portugal	Nuno Pelxinho, University of Coimbra
Spain	Maria Rosa Zapatero Osorio, Centro de Astrobiología
Sweden	Jouni Kainulainen, Chalmers University of Technology
Switzerland	Miroslava Dessauges, Geneva Observatory
United Kingdom	Dannyu Steeghs, University of Warwick
Chile	Sebastian Lopez Morales (co-Chair), Universidad de Chile
Australia	Caroline Foster, The University of Sydney

Table 2. List of special topics and invited speakers at the UC meetings.

Year	Special topic	Invited speakers
2010	ALMA operations	Elisabeth Humphreys, Dirk Petry
2011	APEX operations	Marcus Albrecht, Roberto Maiolino
2012	Public surveys data products	Magda Arnaboldi, Jörg Retzlaff
2013	VLTI operations	Pierre Kervella, Claudia Paladini
2014	Observing Tools	Livia Origlia
2015	ESO Archive	Celine Peroux, Chris Wegg
2016	APEX operations	Claudia Cicone, Helmut Dannerbauer
2017	Multi-object spectroscopy	Barbara Lanzoni, Christophe Adami
2018	ALMA support	Frédérique Motte, Cécile Favre
2019	Public surveys	David Sobral, Sara Lucatello

commissioned, but a close collaboration with the community has rendered it smoother and faster. The large number of ESO instruments and observing modes, however, makes it difficult to maintain pipelines across platforms and include external software (for example, the astronomical software collection Scisoft), especially when resources are shared with other tasks. There is also a strong bimodality between the needs of expert and novice users. The UC has supported data reduction workshops and interferometry schools to engage the community with the new facilities. The Very Large Telescope Interferometer (VLTI) Expertise Centres were established last year to assist new users with preparing VLTI proposals, and to provide advanced support for VLTI data reduction and interpretation.

Communication

The ESO ScienceNewsletter has increasingly become the main source of information for users. This is where Calls for Proposals, data releases, upgrades and major changes to ESO tools, as well as workshops, are announced. Together with The Messenger they are used to increase transparency regarding ESO operations, as requested by the UC and the Visiting Committee. For example, several articles resulted from discussions about whether to change the time allocation owing to its possible effects on efficiency in run completion and therefore on the resulting publications (Primas et al., 2014; Sterzik et al., 2015 and 2016); others refer to encouraging observations in visitor mode (Rejkuba et al., 2018).

Software

The UC has played a major role in prioritising the development of ESO software for Mac OS X, for example, to prepare observations and reduce data. We are also witnessing an increasing usage of the Python coding language. Science pipelines for new ESO instruments are written in Python by instrument consortia and have been developed in parallel at ESO, using ESO tools for quality control purposes. The software language and the possible interface between any two given pipelines for the same application keep the community divided and this remains one of the most highly debated topics at the UC meetings.

What has changed?

Nominations for the Observing Programme Committee (OPC)

One recently acquired task of the UC is to provide nominations of astronomers willing to serve on the OPC. On the one hand, this process has become more transparent to the users, who are contacted directly by their country representative, and on the other hand, this is more efficient for ESO because it has resulted in a significant decrease in the rejection rate during recruitment. UC representatives either scout within their community for suitable astronomers or are approached by astronomers themselves who wish to serve on the OPC. It is also possible to indicate an interest in serving on the OPC via the UC poll. The UC members subsequently populate a database of users from which ESO replenishes the OPC on a regular (currently biannually) basis. Since the UC was entrusted with this task in 2016, the OPC composition better reflects ESO users with respect to gender, seniority and nationality whilst ensuring the broad scientific expertise required to judge observing proposals. Recent regulations on data protection are likely to modify this process and allow the users to enter their personal data directly into an OPC candidate database while the UC members will remain their primary point of contact.

ALMA users

ALMA is a partnership of ESO, East Asia and North America, in cooperation with the Republic of Chile. During the last decade, ESO has acquired an increasing fraction of ALMA users beyond the traditional ESO user community. The procedures to obtain and analyse ALMA data have been integrated into the general ESO operations, after an initial period of dedicated activities. The UC has endorsed this transition and has contributed to unifying the users under one ESO umbrella. UC members are chosen to cover the wide expertise of ESO users. Members with millimetre/submillimetre competence were retained within the UC for more than the standard three-year period to deal with specific ALMA aspects and to make sure that the needs of the new community (like that of ALMA within ESO) were properly addressed. The support from ALMA Regional Centre scientists, the ticketing process, the quality of data products, the feedback on observing proposals, and the archive interface are among aspects that are regularly addressed at UC meetings similarly to those from La Silla Paranal facilities.

Public surveys

Different types of ESO programmes and public surveys gained momentum from the development of the Visible and Infrared Survey Telescope for Astronomy (VISTA), following the UK's joining ESO, and of the Very Large Telescope (VLT) survey telescope. To carry out these programmes ESO users have formed large collaborations, obtained large fractions of telescope time, and are committed to making reduced data products publicly available. On the ESO side, new procedures to prepare the observations and to ingest the data into the archive were also established. Feedback from ESO users involved in public surveys or using data generated from public surveys has been collected and discussed at UC meetings on many occasions, resulting in recommendations, for example to improve the data flow and the associated documentation.

Working groups, boards and reviews

UC members have been involved in specific ESO working groups. For example, the ESO Science Data Management Working Group and the Time Allocation Working Group (see Patat et al., 2018) were established as a result of the ESO 2020 analysis to review the processes involved and to provide suggestions for future implementations. Feedback from both the STC and the UC on the resulting reports was important in planning for changes. The UC agreed with reducing the frequency of calls for proposals to annual calls, coupled with the possibility of a fast-track channel for proposals of limited scope. It also supported the introduction of a filler programme and of a special channel for combined ESO–ALMA programmes. Furthermore, the UC favoured the development of tools for data processing, data mining, data analysis, and data publication to support results obtained from Principal Investigators as well as archive science.

The original reports and the UC feedback are publicly available and were also distributed to the users by their UC representatives. The UC together with ESO formulated the questionnaire about non-publishing programmes (Patat et al., 2017) and more recently also engaged in the review of the ESO data-flow development plan (Hainaut et al., 2018). UC members had an active role on the board for the review of the European ALMA Regional Centre Network Strategic Plan and are regularly invited to join major review panels, for example the Preliminary Design Review of the Multi-AO Imaging CAmera for Deep Observations (MICADO) and Call for Proposals Readiness Review for the 4-metre Multi-Object Spectroscopic Telescope (4MOST).

Forward look

There are obviously many aspects that can be improved, but there are many day-to-day operations to support, and any change to a running system must be planned and implemented carefully in order to avoid disrupting the ongoing operations. It is then a task for the UC to identify which aspects are more relevant for the users and to inform ESO about them, so that priorities can be adjusted to enhance the scientific productivity. Users who plan and build ESO instruments, develop pipelines, observe with ESO telescopes, extract data from the ESO archive, or process and publish scientific results are not necessarily the same users. Therefore, they are not always aware of the distribution of ESO resources to support each of these activities, and sometimes issues may arise as a result of misunderstandings or insufficient information. The UC is a crucial means by which the exchange of information takes place.

The UC's primary interest is in providing feedback on current facilities and services, but it can also provide advice on what the users find important. Improvements in the collaboration between the UC and the STC are envisaged, and also with the respective sub-committees (for example, the La Silla Paranal and the European Science Advisory Committee) which focus more on future developments, but would also consider current facilities and their use.

Users are strongly encouraged to engage with their UC representatives to ensure that their voices are heard. All the comments collected by the UC are passed to ESO in a consolidated way; the format of this feedback may deviate from the diverse formats and ways in which inputs are received from the users. Representing the country in which you work in the UC is a highly valuable experience that I would definitely recommend to you. It enhances your knowledge of ESO activities, and even if you do not need that, it allows you to look at them from a different point of view, taking on board the views of many other users.

Acknowledgements

The author would like to thank the head of the Users Support Department (Marina Rejkuba) and the current chair of the UC (Karina Caputi) for their feedback on an earlier version of this article.

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Links

[1] The Rules of Procedure for the ESO Users Committee: http://www.eso.org/public/about-eso/committees/uc/docs/RoP_UC_new.pdf
[2] ESO's governing bodies webpage: https://www.eso.org/public/about-eso/committees.html

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ESO/M. Claro

The VLT telescopes at twilight, the domes are open in preparation for another night of observations.

Telescopes and Instrumentaion

Construction site of the Extremely Large Telescope on Cerro Armazones in the Chilean Atacama Desert.

G. Hüdepohl (atacamaphoto.com)/ESO

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ELT – Where the Secondary Mirror Becomes a Giant

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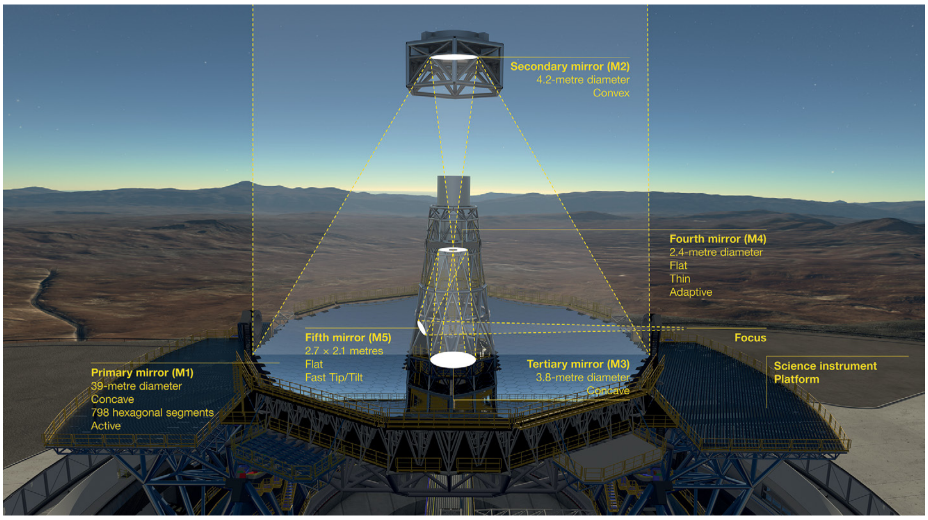

Figure 1. This diagram shows the novel five-mirror optical system of ESO's ELT. Before reaching the science instruments the light first reflects off the telescope's giant concave 39-metre segmented M1 mirror; it then bounces off two 4-metre-class mirrors, one convex (M2) and one concave (M3). The final 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.

The Extremely Large Telescope (ELT) is at the core of ESO's vision to deliver the largest optical and infrared telescope in the world. Following on from our previous Messenger article describing the primary mirror (M1), here we focus on the secondary (M2) and the tertiary (M3) mirrors of the ELT, outlining the complexity and challenges involved, and the current manufacturing status.

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 for imaging and spectroscopy. As shown in Figure 1, the light is collected by the giant 39-metre-diameter M1 mirror and relayed via M2 and M3 (both of which have ~ 4-metre diameters) to M4 and M5, which are the core of the adaptive optics of the telescope. After M5 the light reaches the instruments on one of the two Nasmyth platforms.

This design provides an unvignetted field of view with a diameter of 10 arcminutes on the sky, an area of ~ 80 square arcminutes (1/9 the size of the full moon on the sky). Thanks to the combined activation of M4 and M5, the ELT will be able to correct for both atmospheric turbulence and the vibration of the telescope structure itself induced by motion and wind. This is crucial to enabling the ELT to reach its diffraction limit, which is ~ 8 milliarcseconds (mas) in the *J*-band (at $\lambda \sim 1.2$ μm) and ~ 14 mas in the *K*-band, thereby providing images 15 times sharper than the Hubble Space Telescope.

Translated into astrophysical terms, this means opening up new discovery spaces, from exoplanets close to their host stars, to black holes, to the building blocks of galaxies – both in the local Universe and billions of light-years away. Specifically, the ELT will be able to detect and characterise extrasolar planets in the habitable zone around our closest star, Proxima Centauri, and resolve giant molecular clouds (the building blocks of star formation) down to ~ 50 pc in distant galaxies at redshifts $z \sim 2$, as well as even smaller structures in sources that are gravitationally lensed by foreground clusters — all with an unprecedented sensitivity.

The secondary (M2) and the tertiary (M3) mirrors

The ELT's M2 mirror, with its 4.25-metre diameter, will, like many aspects of the ELT, set another record in the astronomical landscape. M2 will be the largest secondary mirror ever used on a telescope, and the largest convex mirror ever produced. For comparison, the secondary mirrors on the 8-metre VLT Unit Telescopes are just over 1 metre in diameter. Even more impressively, M2 is larger than the primary mirror of the VISTA telescope and indeed the primary mirrors of many other telescopes that are operating today. There is also the added challenge that M2 will hang upside-down over the 39-metre M1 mirror, about 60 m above the ground, held in mid-air by its support structure (called the M2 cell) and anchored to the telescope main structure. The M3 mirror is similarly large and complex, with its 4-metre diameter. The mirrors alone weigh more than 3 tonnes each; with the cell and structure the overall weight of each assembly is about 12 tonnes.

Both M2 and M3 are produced by the German company SCHOTT and are made of a special low-expansion glass-ceramic material called ZERODUR®. This special material is ideal because it is not sensitive to thermal fluctuations thanks to its very low thermal expansion coefficient. This means that the form and the shape of the mirrors will not change significantly with temperature during observations. This material is also extremely resistant; it can be polished to the required finishing level and has been used in telescope mirrors for decades.

The manufacture of the M2 and M3 mirrors is a great example of the strong collaboration between ESO and European industries. The production of the blanks is being carried out by the German company SCHOTT, the final polishing of the surface by the French company Safran Reosc, and the cells to hold the mirrors will be made by the Spanish company SENER.

Challenges with M2 and M3

The M2 mirror is a convex 4.25-metre F/1.1 thin meniscus, about 100 mm thick, with an 800-mm central hole. Its optical surface shape is very aspheric, with a departure from a sphere that is close to 2 mm. The size, convexity, aperture ratio and asphericity make this mirror extremely difficult to polish and test.

The M3 mirror is a concave 4.0-metre F/2.6 thin meniscus, about 100 mm thick, with a 30-mm central hole. Its optical surface shape is mildly aspheric, with a departure from a sphere of only about 30 μm. Besides its 4-metre size, the M3 mirror is easier to manufacture and test compared to the M2, and the required M3 mirror production and metrology processes are more common.

The M2 and M3 mirror blanks (i.e., the "glass" made by SCHOTT) weigh about 3 tonnes each, and require sophisticated production methods and processes. After an initial raw material casting in a cylindrical mould, each blank is carefully cooled down and annealed for about three months, so as to maximise the material's homogeneity, and minimise the internal stresses and the number of bubbles and inclusions. The resulting glassy boule then undergoes a six-month heat treatment to transform the material into glass-ceramic and adjust the near-zero coefficient of thermal expansion to a few parts per billion accuracy. Each blank is then machined to its final geometry, and acid etched to remove residual subsurface damage and maximise the mirror strength.

The blanks are then transported to Safran Reosc for figuring and polishing, in the same facilities where the 8-metre VLT primary mirrors were polished in the 1990s.

Figure 2. This image shows some of the people behind the scenes at the technical acceptance of the massive 3-tonne blank for the ELT's M2.

These facilities have been refurbished to accommodate the specific requirements of figuring and testing M2 and M3. Each blank follows the same finishing process: adhesive bonding of the invar interface pads, and then a series of steps to achieve the final surface quality; grinding and fine grinding to an accuracy of a few μm, followed by polishing and figuring to an accuracy of a few nm — about 20 000 times thinner than a human hair. Both the grinding and polishing processes rely on a combination of small tool figure correction and mid-size tool smoothing on a dedicated 4-metre figuring machine. At the grinding stage the mirror figure is monitored using a 4-metre 3D coordinate measurement machine (3D CMM).

Interferometry testing through null correctors has been developed for polishing, using a giant Fizeau Test Matrix for M2 and computer-generated holograms (CGH) for M3. Both mirrors are supported on dedicated active metrology mounts during figuring to accurately match the force distribution in the mirror cells' support. Each mirror requires about two years for figuring and polishing, not including the time needed to upgrade the facilities, the production of testing equipment and commissioning.

Both M2 and M3 mirrors are hosted on the telescope in dedicated cells, which provide shape adjustment capability to compensate static errors to some extent and position control for locating the mirrors within the telescope. The overall weight of each assembly (mirror and cell) is about 12 tonnes and the requirements to position such a massive structure are really challenging — despite the weight, the requisite accuracy of the positioning stage is on the order of just 0.1 mm.

The cells for M2 and M3 have similar design concepts. Each mirror is axially supported on its back surface with an 18-point whiffletree, and laterally at 14 points on the mirror's outer edge. As the M3 mirror is away from any pupil, the active correction of this mirror is mandatory. On the other hand, low-order deformations of the M2 mirror have very limited error propagation in the field, so the active shaping of M2 is implemented as a provision only.

In order to align the M2 mirror with respect to the rest of the optics (M1, M4, M5), the whole assembly will be moved relative to the telescope structure using six position actuators (hexapod). Three actuators are oriented along the mirror optical axis, the three others are located within the plane of the centre of gravity, as shown in Figure 3. It is worth noting that the relative accuracy of this hexapod, which will move every few minutes, is in the sub-μm range, which presents a real challenge.

M2 and M3 in the making

After sixteen months of manufacturing, the M2 mirror blank was completed by the SCHOTT company and accepted in December 2018 (see Figure 2). It was then stowed in its transport container and shipped to France for the final polishing by Safran Reosc in its refurbished facilities. The VLT M1 facilities have been modified by Safran Reosc to host the M2 and M3 mirrors. All aspects related to their production have been designed, procured, and installed and are being commissioned at the time of writing. The metrology facilities are complete and ready for the grinding phases. The interferometric metrology facilities are in the final stages of manufacturing. Grinding of the M2 mirror started in March 2019.

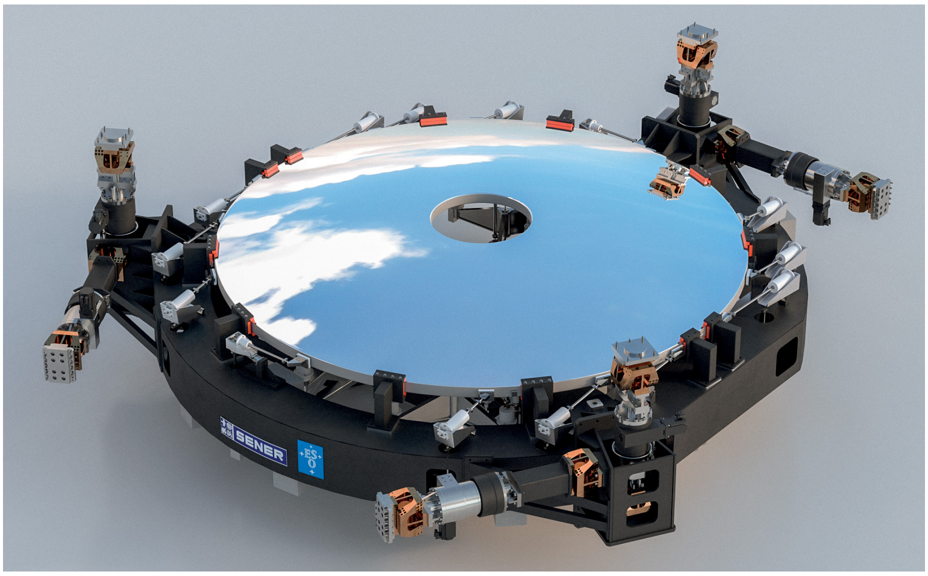

Figure 3. Rendering of the M2 mirror in its mirror cell.

The M3 mirror blank has also been cast and is now in its final stages of manufacturing; it is expected to be completed in line with contractual deadlines. The design of the cells is also progressing well at SENER and has successfully passed Preliminary Design Review (Figure 3).

SCHOTT

The M2 blank of the ELT being transported to France for final grinding and polishing by Safran Reosc.

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MUSE Narrow Field Mode Adaptive Optics Science Verification

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The Narrow-Field Mode (NFM) on the Multi Unit Spectroscopic Explorer (MUSE) uses laser tomography to correct for atmospheric turbulence at optical wavelengths. Science verification of this new mode of the MUSE instrument took place in September 2018. The science verification observations were obtained in service mode. Out of 37 submitted proposals, 16 observing programmes were scheduled for a total of 43.5 hours of observations. The allocation assumed a seeing better than 0.8 arcseconds, i.e., the required atmospheric conditions to achieve effective adaptive optics correction. Some of the top priority programmes could not be executed because the reference stars were too faint to provide sufficient low-order adaptive optics corrections. As shown by the first results presented here, the NFM will enable advances across a range of scientific areas, for example, characterising substellar/planetary mass objects, globular clusters, and active galactic nuclei.

Proposal solicitation and submission

The call for science verification proposals using MUSE NFM adaptive optics (AO) was issued on 30 April 2018[1]. It was published in the ESO Science Newsletter[2] on that day, as was the corresponding science verification webpage[3]. By the deadline on 30 May 2018 37 proposals were received, requesting a total of 97 hours. The science verification team ranked the proposals according to scientific relevance and at the final selection meeting on 20 June, 16 projects were selected for a total of 43.5 hours of execution time.

The proposers were informed about the outcome of the selection on 26 June 2018. The Phase 2 deadline was 20 July 2018. During Phase 2 preparations one of the top-ranked projects had to be discarded as no reference guide star was available in the field, reducing the allocated time for science verification observations to 35 hours.

A wide range of science targets were allocated time. They include: discs in T Tauri stars; Jovian moons; a circumbinary exoplanet; globular clusters; a black hole in a stellar cluster; ultracompact H II regions; a nearby supernova; merging galaxies and luminous infrared galaxies; binary supermassive black holes; candidate gravitational lenses from Gaia; and strongly lensed quasars.

Observations

The MUSE NFM science verification nights were scheduled from 7 to 11 August 2018. However, the observations could not take place as planned because of the failure of one of the lasers in the 4 Laser Guide Star Facility and the run had to be postponed until early September 2018. Paranal science operations accommodated extra time in service mode and the rescheduled science verification observations took place between 5 and 18 September 2018 (mostly during half-nights).

A strong constraint for MUSE NFM observations is good seeing conditions, so any time with seeing > 0.8 arcseconds would have resulted in inadequate corrections and was returned to regular service observing. It was agreed that the total allocated time for science verification on MUSE NFM should be a maximum of 30 hours given the fact that the science verification observations would use the best seeing conditions. In the end a total of 27 hours were used for science verification observations.

Of the 15 scheduled programmes, five could be completed and six received partial data. Two additional programmes were attempted but could not be observed owing to the absence of adequate natural guide stars (either they were too extended or the on-axis tip-tilt reference star turned out to be a double star) and two programmes were not started at all. All proposers were informed about the outcome of their observations on 19 September 2018.

Archive and data processing

All raw science verification data are publicly available through the ESO science archive. The MUSE NFM AO science verification webpage contains direct links to the raw data in the archive[4]. The science verification webpage also provides a link to the data reduction pipeline together with detailed instructions on its installation. The new pipeline includes the OCA rules[a] specific to the NFM and the pipeline can be run within the ESO Reflex workflow (Freudling et al., 2013).

First science results

We present a few science results that have been achieved with science verification data and demonstrate the capabilities offered by this new mode.

Circumbinary planet/brown dwarf

The recently discovered circumbinary object 2M0103 b has a mass that lies at the planet/brown dwarf boundary (Delorme et al., 2013; Janson et al., 2017). The MUSE NFM imaging quality is demonstrated by the clear separation of the central components of the binary A and B at < 200 milliarcseconds. The observations were taken in good conditions (outside seeing ~ 0.6 arcseconds and a coherence time τ_0 ~ 4 ms and the source as reference star with $H = 9.6$). The two stars are fully resolved. The faint low-mass companion can be easily distinguished from the residual point spread function halo of the central pair, which would not be possible without the high AO quality. The RGB image in Figure 1 has been generated from the MUSE data cube. This emphasises the extreme redness of the cold substellar companion relative to the central M-dwarf binary. A full analysis of the spectra and astrometry of both the central binary and the substellar companion is in preparation.

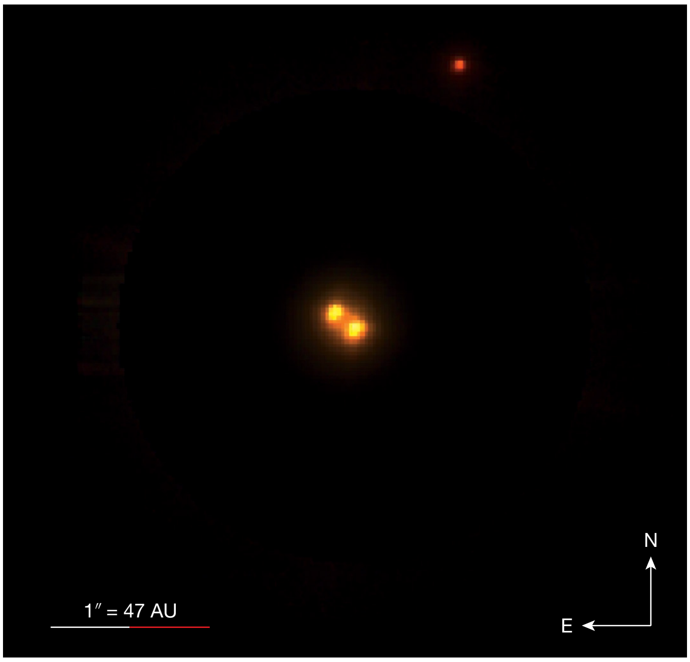


Figure 1. *RGB* image of a circumbinary low-mass object, either an exoplanet or brown dwarf. The central parts of the image have been scaled down in flux by a factor of 200 relative to the outer parts in order to display all components of the system simultaneously.

Globular Cluster

NGC 6440 is a massive ($M = 4 \times 10^5\ M_{\odot}$) Galactic globular cluster located at 8.5 kpc in the direction of the Milky Way bulge. The extremely large stellar density in the core ($\log \rho_0 = 10^6\ M_{\odot}\ \mathrm{pc}^{-3}$) prevented an appropriate exploration of its innermost kinematics so far. The unprecedented characteristics of MUSE NFM have been exploited to finally probe the internal kinematics of NGC 6440.

Figure 2 illustrates the potential of MUSE NFM observations. The ground-based data achieved an angular resolution comparable to that of the Hubble Space Telescope. From these observations, spectra of more than 1500 resolved stars could be extracted and more than 900 stars have been measured in the innermost 4 arcseconds from the cluster centre (see example spectra in Figure 3).

This demonstrates that with MUSE the radial velocity of hundreds of individual stars can be measured in the innermost core regions of high-density systems at sub-arcsecond scales, opening the possibility of properly exploring the internal kinematics of Galactic globular clusters where a variety of complex dynamical phenomena are expected to occur.

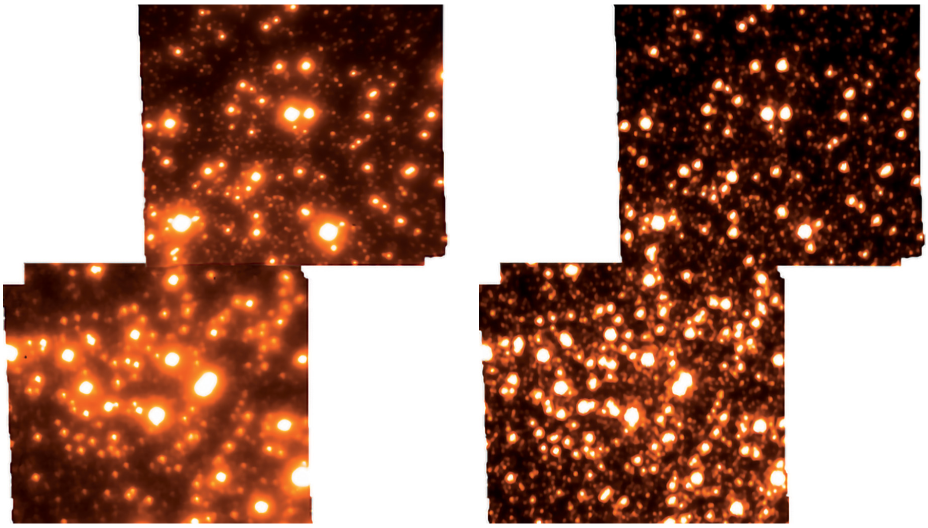
M54 in the Sagittarius dwarf spheroidal galaxy

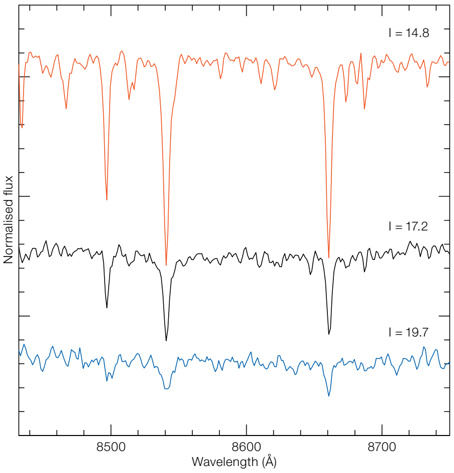
This massive cluster at the nucleus of the dwarf spheroidal galaxy provides the chance to explore the inner kinematics and to search for a potential intermediate-mass black hole. It has been observed in all three MUSE modes (natural seeing, wide-field mode, and now the narrow-field mode). Images of M54 with the two MUSE AO modes can be seen in Figure 4. The increased angular resolution makes many more stars accessible, which had previously been blended. Spectra of about 400 stars with sufficient signal to measure radial velocities and perform a population analysis can be extracted from the NFM data. Within the inner 3 arcseconds (corresponding to about 0.4 pc) over 200 stars can be used for this analysis. Discrete Jeans modelling of M54 will be performed with the three MUSE datasets. Already, three different sub-populations of this nuclear star cluster can be distinguished well into the central regions. The search for the intermediate-mass black hole continues using these data.

Host galaxy of superluminous supernova

Superluminous supernovae (SLSNe) are among the most luminous stellar explosions. Most SLSNe have been detected in star-forming dwarf galaxies. The environment of the hydrogen-rich SLSN PTF10tpz is remarkable in that

Figure 2. Comparison between a mosaic of two reconstructed MUSE NFM images (left) and an HST/WFC3 image (right) of the innermost region of the massive globular cluster NGC 6440.



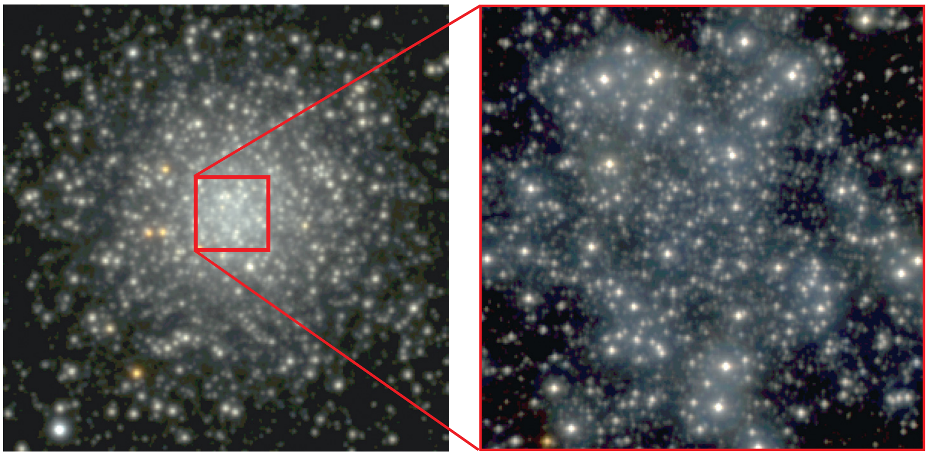


Francesco Ferraro

Figure 3. Examples of MUSE NFM spectra in the calcium triplet region for three stars with different luminosities: a main-sequence-turnoff star (blue), a red giant at the level of the horizontal branch (black) and a very bright giant in the region of the red giant tip (red). These lines are perfectly suited to measuring stellar radial velocities, from which the velocity dispersion profile and, potentially, the rotation curve of the cluster can be determined.

respect; not only is the host an Sa/S0-type galaxy, but AO imaging with the Keck telescope revealed that the transient is only 250 pc (0.3 arcseconds) from the galaxy nucleus. This raises the question of how massive stars, which are thought to be progenitors of SLSNe, can be formed so close to galaxy nuclei. Is star formation enhanced because of active galactic nucleus (AGN) feedback, or are these star-forming regions clumps formed inside the AGN outflow?

The MUSE data of the host of PTF10tpz show a ring-like structure rotating around the galaxy centre. Emission-line regions are detected throughout this structure. Assuming that this emission is connected with star formation, Figure 5 shows a two-dimensional map of the star formation rate (after correcting for Galactic and host-internal reddening). The progenitor of PTF10tpz was formed in this ring, but not in the region with the highest flux. A detailed analysis will test whether an AGN jet could be interacting with this ring and what the properties of the stellar population(s) and the progenitor of hydrogen-rich SLSNe are. This observation demonstrates that MUSE NFM has great potential to provide new constraints on the progenitors of transients.



Mayte Alfaro

Figure 4. MUSE WFM AO and NFM observations of M54. The WFM image covers 1 × 1 arcminutes and the red box has dimensions of 7.5 × 7.5 arcseconds.

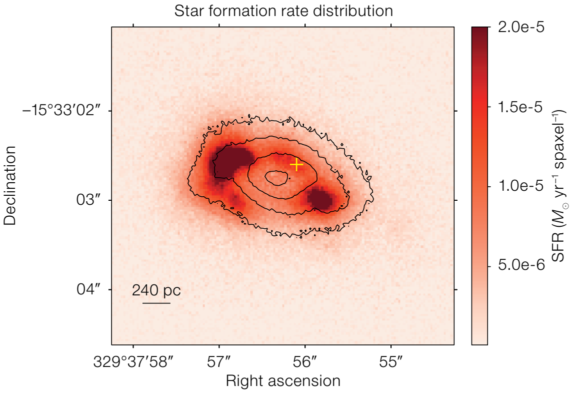
Starburst–AGN connection

The influence of a supermassive black hole on its surroundings can be dramatic. It can trigger nuclear star formation and also influence the galaxy as a whole. At the same time, the exact process fuelling the black hole is unclear and more detailed observations are needed to explore these connections. NGC 7130 is a luminous infrared galaxy that displays signatures of an AGN as well as nuclear starburst activity.

The MUSE NFM observations (Knapen, Comerón & Seidel, 2019) have now revealed a small kinematically decoupled core with a radius of 0.2 arcseconds; this could be a very small nuclear disc. In addition, an outflow can be seen towards the north-west, possibly a jet emanating from the AGN. The outflow shows emission line ratios characteristic of AGN, an enhanced velocity dispersion and non-circular gas velocities (see Figure 6). It is roughly perpendicular to the plane of the host galaxy disc. This analysis used only the best observations (with seeing < 0.6 arcseconds and $\tau_0 > 6$ ms).

Summary

Unsurprisingly, the AO corrections vary critically depending on the atmospheric conditions and the brightness of the natural reference star. Users need to be aware that they need good conditions (seeing better than 0.8 arcseconds) to achieve a decent AO correction. The current limit of the reference tip-tilt star is 14 magnitude in H in regular conditions, or $14 < H < 15$ under very good conditions (i.e. 0.6-arcsecond seeing as specified at Phase 1) and represents a significant restriction on the available science. Several of the highest-ranked projects could not be executed because of inadequate AO correction caused by the faintness of the natural reference star. A pro-



Steve Schulze

Figure 5. Star formation rate map of the inner region of the host galaxy of the hydrogen-rich superluminous supernova PTF10tpz (its position is marked by +). The inner region of the S0/Sa-type galaxy reveals a rotating ring-shaped emission-line region. Assuming that these lines are powered by ionising radiation from star-forming regions, the line fluxes were converted into a star formation rate (SFR). Intriguingly, the superluminous supernova did not explode in the brightest part of the ring complex. The contour lines indicate the distribution of the continuum emission extracted from the MUSE data.

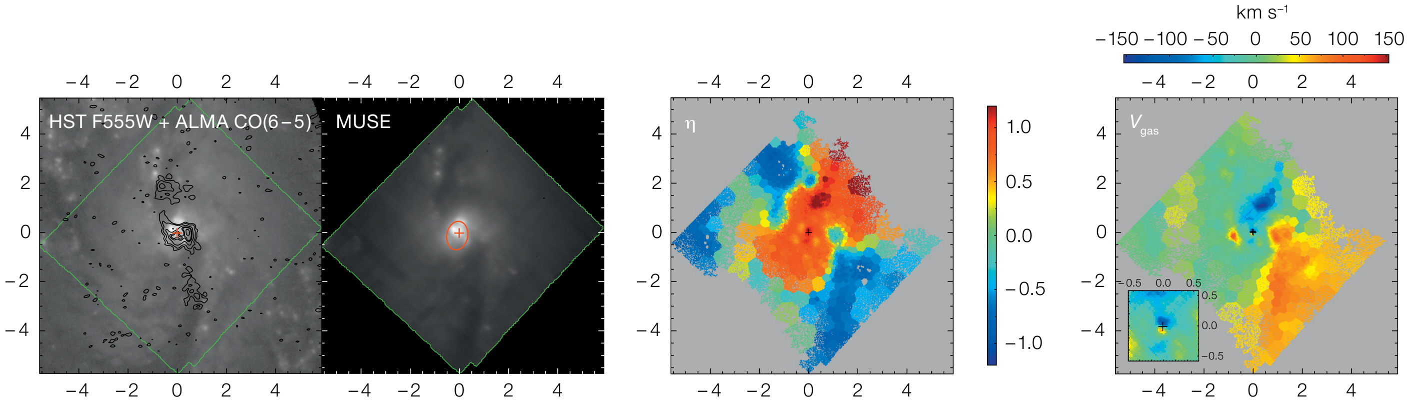


Figure 6. Comparison of the molecular gas (from ALMA) and inner galaxy of NGC 7130 (HST image) and the image produced from the collapsed MUSE data cube (left panel). The middle panel shows shock-dominated regions (in red) and star formation regions (in blue) derived from the [O III]/Hβ and [N II]/Hα line ratios. The velocity dispersion (right panel) displays a kinematically decoupled region around the core (inset) and potentially, an outflow (blue-shifted material) towards the north-west. A kinematically decoupled region around the core can be seen in the inset of the right panel. This figure has been adapted from Knapen, Comerón and Seidel (2019). Coordinate labels are in arcseconds. North is up and east is to the left.

ject to increase the limiting magnitude by employing a different detector in GALACSI, MUSE's AO facility, has begun and will extend the brightness limit by about 2 magnitudes, enabling many more objects to be observed using MUSE NFM.

Acknowledgements

We received excellent support at the telescope from the Telescope and Instrument Operators. In particular, they accommodated the science verification observations flexibly when they had to be postponed for technical reasons. We would like to thank the following Principal Investigators who kindly provided the preliminary science verification results presented in this article: Markus Janson, Francesco Ferraro, Mayte Alfaro, Steve Schulze and Marja Seidel.

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Links

[1] Call for MUSE NFM science verification proposals: http://www.eso.org/sci/publications/announcements/sciann17110.html
[2] ESO Science Newsletter from April 2018: http://www.eso.org/sci/publications/newsletter/apr2018.html
[3] MUSE NFM science verification webpage: http://www.eso.org/sci/activities/vltsv/musenfmsv.html
[4] Access to science verification data: http://www.eso.org/sci/activities/vltsv/musenfmsv.html#data

Notes

[a] OCA stands for organisation, classification and association, and refers to rules which allow: the classification of raw data according to the contents of the header keywords; their organisation into appropriate groups for processing; and association with the required calibration data for processing.

ESO/Daniele Gasparri (www.astroatacama.com)

The adaptive optics system of Yepun (Unit Telescope 4 of the VLT) in operation.

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Orion-KL Observations with the Extended Tuning Range of the New SEPIA660 APEX Facility Instrument

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During Science Verification of the new SEPIA660 facility receiver at APEX, we carried out a shallow line survey of the archetypal Kleinmann-Low Nebula in the Orion star forming region (Orion-KL). These observations cover the tuning range towards the band edges, which has recently been extended beyond ALMA Band 9 specifications. At these frequencies, atmospheric transmission is very low but still sufficient to detect bright lines in Orion-KL. We present the collected spectra and compare with surveys from the literature, demonstrating the capabilities of the instrument.

High frequency submillimetre observations

Submillimetre radiation from space is severely absorbed by water vapour molecules in the Earth's atmosphere. This is why ground-based submillimetre astronomy is exclusively conducted at high and extremely dry places in the world, where the integrated column of precipitable water vapour (PWV) is itself submillimetric. The Chajnantor plateau over the Chilean Andes in Chile Is one of the most outstanding sites available and is where the Atacama Pathfinder Experiment (APEX)[a,1] has been successfully operating for more than a decade, joined more recently by the Atacama Large Millimeter/submillimeter Array (ALMA).

The state-of-the-art instrumentation at these observatories is designed to take advantage of several well-defined spectral windows in which atmospheric transmission is high (see Figure 1), allowing the detection of molecular and atomic transitions to high redshifts, including CO, HCN, HCO+, [C II], [O I]. It is particularly challenging to detect interstellar water, as extremely dry atmospheric conditions are required. Instrumentation groups therefore have to meet the challenge of producing sensitive detectors and spectrometers with large bandwidths in order to exploit premium weather conditions, thus facilitating the study of objects at these wavelengths.

New facility instrumentation at APEX

SEPIA is a multi-receiver instrument (Belitsky et al., 2018) developed by the Group for Advanced Receiver Development (GARD)[2] at Chalmers University in Sweden. It comprises ALMA Bands 5, 7 and 9 (see Figure 1 for their frequency coverage). The SEPIA180 dual-polarisation receiver covers frequencies 159–211 GHz and was installed at APEX in 2015. This is an ESO-OSO Principal Investigator receiver but is offered to APEX user communities of all APEX partners, including Chile. One of its main goals is to observe the 183.3 GHz water transition and high redshift CO lines. The SEPIA345, also

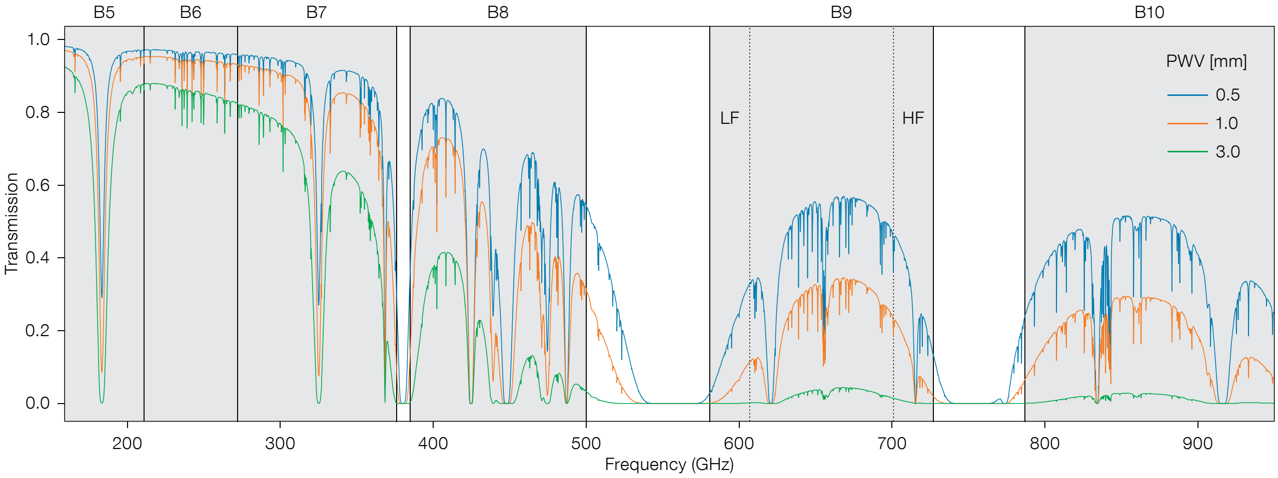

Figure 1. Atmospheric zenith transmission over Chajnantor by Pardo et al. (2001), between 150 and 950 GHz with different amounts of PWV. The spectral coverage of the ALMA bands is indicated along the top axis, as well as the low-frequency and high-frequency ranges of the SEPIA660 band covered in this survey.

developed by the GARD team, will likely be delivered in 2020 as a facility receiver. This is a dual-polarisation, two-sideband (2SB) receiver and will cover the frequency range 275–373 GHz, with a simultaneous bandwidth of 8 GHz. More recently, the SEPIA660 receiver was developed by the NOVA instrumentation group in Groningen. It was installed and commissioned in 2018 and has become the first of the second generation of facility instruments at APEX.

In 2020, APEX will also host another facility receiver, the new FaciLity APEX Submillimeter Heterodyne instrument (nFLASH), which is currently being assembled by the Max-Planck-Institut für Radioastronomie (MPIfR) instrument development group in Bonn. This will be a powerful dual-band, dual-polarisation 2SB receiver operating simultaneously over the 230-GHz and 460-GHz frequency windows, also possessing an 8 GHz intermediate frequency bandwidth.

SEPIA660 is an upgraded version of the former SEPIA Band 9 receiver that was integrated at APEX in 2016. The new incarnation was installed and commissioned in the second half of 2018 and comes with important improvements, such as 2SB mixers (see Hesper et al., 2017; 2018) with high sideband rejection (> 20 dB), dual polarisation, and an extended tuning range from 581 to 727 GHz. After technical commissioning a call for Science Verification[3] projects was released inviting programmes that could demonstrate the new capabilities of the receiver. In this context the observations presented here were conceived to verify the performance of the receiver in its extended tuning range.

Orion-KL: a laboratory for astrochemistry

Given the low atmospheric transmission at the edges of the SEPIA660 frequency window, we decided to observe one of the brightest and better-known star-forming regions, Orion-KL (Kleinmann & Low, 1967), where a good number of bright transitions are expected even in a relatively short exposure. Because of the dense line forest in almost all mm and sub-mm windows, Orion-KL is a key reference target used to monitor instrument performance and is observed regularly for cross calibration of science programmes.

Line ID	f_{sky} [GHz]/SB	Signal band	f_{LO}	Image band
F583L	583.0 LSB	581–585	589.0	593–597
F585L	585.0 LSB	583–587	591.0	595–599
F587L	587.0 LSB	585–589	593.0	597–601
F589L	589.0 LSB	587–591	595.0	599–603
F591L	591.0 LSB	589–593	597.0	601–605
F593L	593.0 LSB	591–595	599.0	603–607
F715U	715.0 USB	713–717	709.0	701–705
F717U	717.0 USB	715–719	711.0	703–707
F719U	719.0 USB	717–721	713.0	705–709
F721U	721.0 USB	719–723	715.0	707–711
F723U	723.0 USB	721–725	717.0	709–713
F725U	725.0 USB	723–727	719.0	709–713

Table 1. List of the 12 spectral setups used in the survey, including the local oscillator frequencies as well as the frequency coverages for both sidebands. All frequencies are in GHz.

Orion-KL is the nearest region in which high-mass stars are being formed and is located 415 pc from the Sun (Menten et al., 2007). Given its vicinity, brightness and chemical complexity, Orion-KL has been used for years as a cosmic laboratory to study the chemistry of high-mass star forming regions. This area contains a good number of embedded young stellar objects that have also been extensively targeted by many ground- and space-based facilities. Examples include deep observations at X-ray wavelengths with Chandra (Getman et al., 2005); in the mid-infrared with Keck (Shuping et al., 2004); in the near infrared with the Son of Isaac (SofI) on the NTT (Muench et al., 2002) and at centimetre wavelengths with the Karl G. Jansky Very Large Array (VLA; Forbrich et al., 2016).

Much earlier VLA observations of this field had already revealed the presence of several compact radio sources, some of which are counterparts of known infrared sources. Source I was found to be associated with SiO maser emission, which is unusual amongst young stellar objects. Extensive follow-up observations have been made of this object, one of the more massive and more luminous in the region (see for example, Hirota, Kim & Honma, 2016, and references therein). Close to Source I is SMA1 and source n. The former is detected at submillimetre wavelengths but not at X-ray or centimetre wavelengths; this is probably due to its being one of the youngest members in the evolving cluster. Source n has a double-peaked morphology and like source I is moving southwards within the cluster (Rodríguez et al., 2017).

In this work, we targeted the coordinates of source I (05:35:14.5-05:22:31.0) and our spatial resolution element is given by the antenna half-power beam width (HPBW), which ranges between 8.6 and 10.7 arcseconds at the observed frequencies. Thus, our beam area covers emission from the complex inner region from which strong molecular outflows in Orion-K are likely to originate and also includes the hot core, source n and SMA1. Other strong sources in the cluster, like the Becklin-Neugebauer object (Becklin & Neugebauer, 1967) or the compact ridge, should be outside the beam coverage.

Several line surveys of this complex have been published in the literature at submillimetre wavelengths, like the Caltech Submillimeter Observatory (CSO) observations published by Schilke et al. (2001) which cover the frequency range 607–725 GHz, partially overlapping with our SEPIA660 observations, or observations from the Heterodyne Instrument for the Far Infrared (HIFI) on the Herschel Space Observatory in the framework of the Key Program, Herschel observations of EXtraOrdinary Sources (HEXOS; Crockett et al., 2014).

SEPIA660 observations

The Orion-KL observations were carried out on 13 October 2018 over almost three hours, including pointing, focus, calibrations and the spectral survey. Weather conditions were not ideal for submillimetre observations (PWV was 0.7 mm) but were sufficiently good to

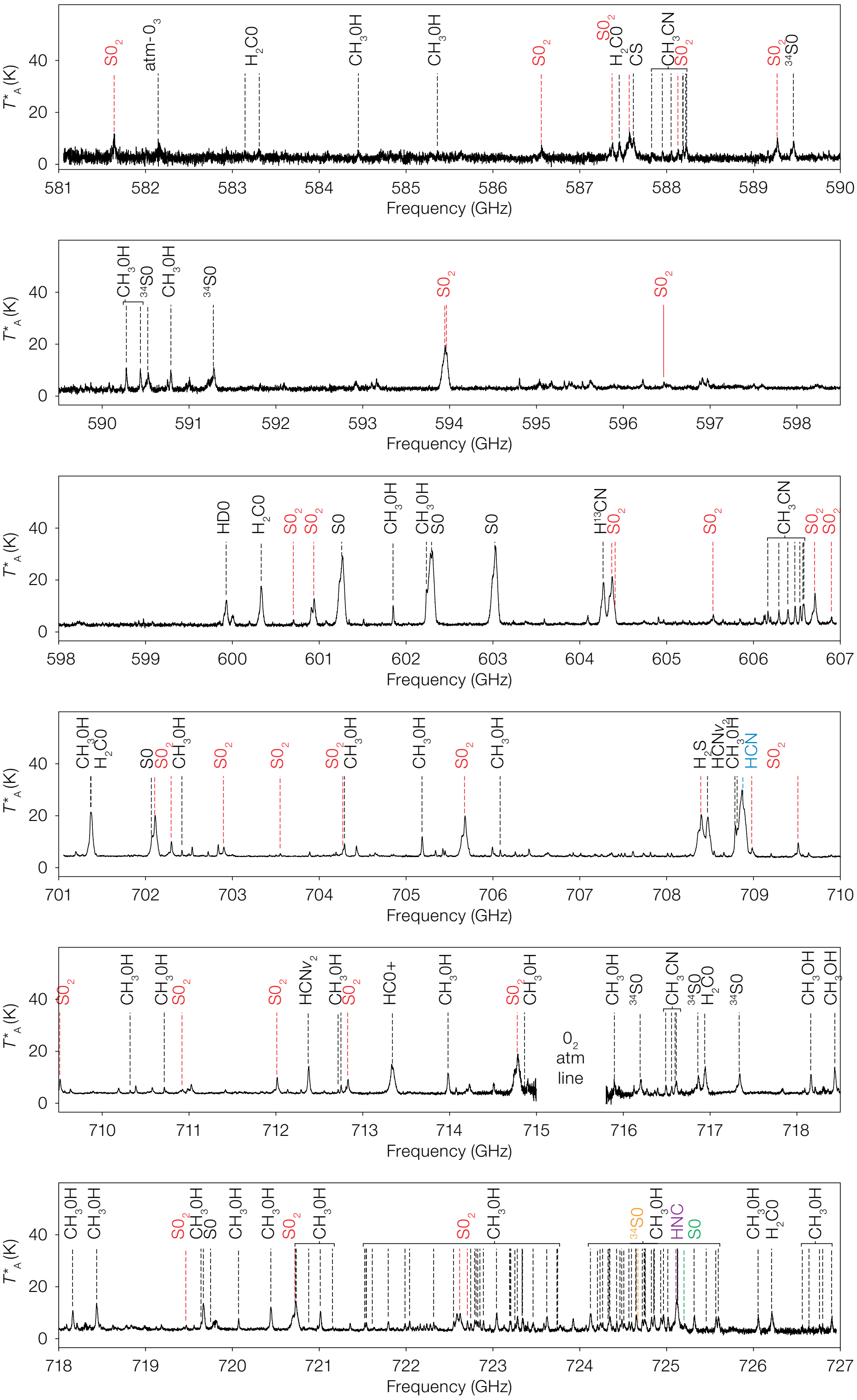

Figure 2. The composite spectrum observed with SEPIA660. The three upper panels correspond to the low-frequency coverage, and the lower ones to the high-frequency window. The most prominent detected lines of selected molecules have been labelled. The portion between 715 and 716 GHz was removed for clarity as it corresponds to severe absorption by atmospheric O_2.

detect the brightest lines in our target. We covered the sky frequencies between 581 and 595 GHz with six spectral setups. Each setup covers 4 GHz in the signal band (and 4 GHz in the image band) and overlaps with the next one by 2 GHz. A similar strategy was followed over the high-frequency range, 713 to 722 GHz (see Table 1 for details).

This approach guarantees homogeneous coverage of all of the low and high frequency ranges (581–607 and 701–727 GHz, respectively), combining the two sidebands. Each tuning was observed for 60 seconds, so each part of the spectrum was covered twice thanks to the frequency overlap between adjacent tunings.

We used the wobbling secondary at a rate of 1.5 Hz to remove the contribution from atmospheric emission. We switched from the target with an azimuthal amplitude of +/– 150 arcseconds in symmetric mode. Since none of the signal or image bands include CO lines, contamination from the off position should not be an issue for the great majority of spectral lines detected.

The datasets were initially calibrated online by the APEX calibrator software, which uses a single opacity correction over each 2.5 GHz segment of the backend. The atmospheric variation in the observed bands requires a finer frequency grid for the opacity calibration correction to effectively remove the atmospheric features. Therefore, we re-calibrated the data channel-wise offline (each channel corresponds to ~ 0.08 MHz). This vectorised method was recently implemented by our online calibrator software and from 2019 onwards has become the default method applied to all APEX data. We compared the online and offline calibration and could verify that the channel-wise approach substantially improves the calibration around the 715.4 GHz molecular oxygen line and a few of the strongest ozone lines. We note, however, that owing to the very low transmission at the lower end of the low-frequency window, the calibration is not able to fully remove the atmospheric ozone line at 582.14 GHz.

In order to produce the final spectra, we removed the outermost 50 MHz at the edges of the band and 100 MHz in

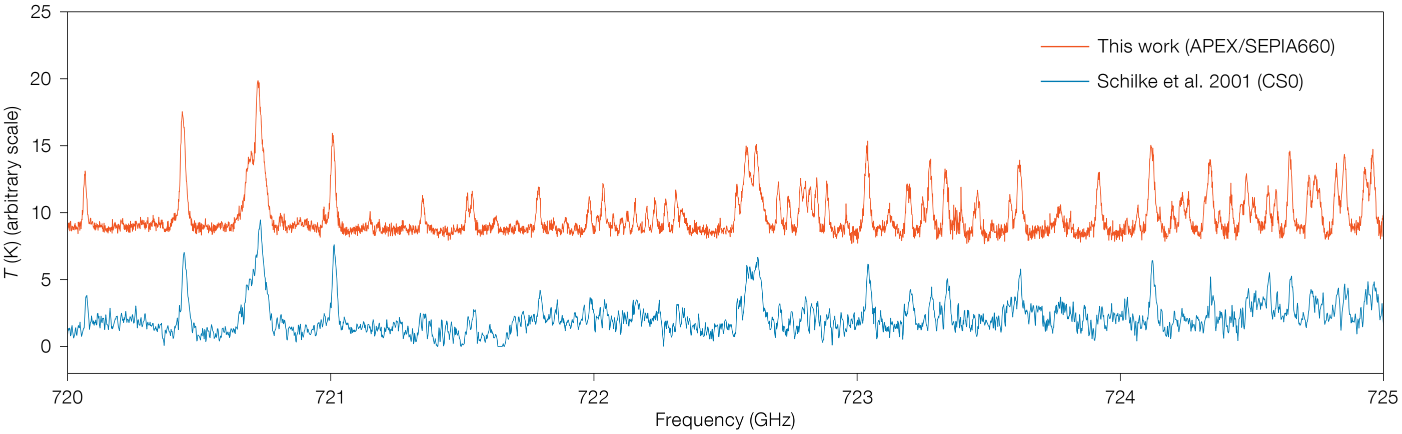

Figure 3. A selected portion of the SEPIA660 spectrum and comparison with a similar dataset by CSO (Schilke et al., 2001). The temperature scale is arbitrary, and an offset between the spectra has been introduced to enable comparison.

the overlap region to avoid the aliasing effects of the spectrometers. Spectra have been resampled from their original spectral resolution to 0.5 km s^{-1} which corresponds to about 1 MHz.

Results and comparison with literature

Figure 2 shows the composite spectrum of the two spectral windows observed. In the low-frequency window (upper three panels), a gradual increase of noise towards lower frequencies results from the increase in atmospheric opacity. For the same reason the higher signal-to-noise corresponds to frequencies between 700 and 710 GHz. More precisely, the noise level is around 1 K root-mean-square in the range 580–585 GHz and ten times lower at 702—704 GHz. There is substantial continuum emission over the band and we have not subtracted any baseline to the spectra shown in Figure 2.

It is beyond the scope of this article to make a complete census and characterisation of molecular transitions; rather we show the most prominent transitions from the species that are known to exist in this region, and compare these with previous existing data in the literature. We have added labels in Figure 2 to the strongest lines detected in our survey: mostly vibrationally excited transitions from methanol (CH_3OH), methyl cyanide (CH_3CN), formaldehyde (H_2CO), sulphur oxides (SO, SO_2, ^{34}SO), deuterated water (HDO), hydrogen cyanide (HCN), isocyanide (HNC) and formylium (HCO^+).

In Figure 3, we compare a portion of our spectrum with the same frequency coverage published by Schilke et al. (2001), taken with the 650-GHz facility dual-sideband (DSB) receiver at the CSO. The CSO observations cover the same region as ours and use a similar beam size (~ 11 arcseconds) so this is an ideal dataset for comparison. Our SEPIA660 spectrum, resampled to 0.5 km s^{-1} perfectly matches the 1 MHz resolution of the CSO data. Since the CSO receiver had DSB mixers, both sidebands are superposed in the final spectrum. In order to separate these, Schilke et al. (2001) had to observe several spectra with different local oscillator frequencies and then apply a maximum entropy deconvolution algorithm. Because SEPIA660 is a 2SB receiver, both sidebands are recorded separately, and no extra deconvolution is needed. In addition, the high sideband rejection ratio ensures minimum contamination from the signal (and noise) between sidebands. Even if the root-mean-square noise per channel is comparable in both APEX and CSO spectra, Figure 3 shows that the baseline of the APEX/SEPIA660 spectrum is much flatter and that weaker lines are detected with higher signal-to-noise ratios.

The part of the spectrum between 725 and 727 GHz that is not covered by the CSO observations from Schilke et al. (2001) is shown in red in Figure 4. This is the last tuning in our frequency range and has only half of the integration time (60 seconds with no overlap). In addition, atmospheric transmission is very low (< 10%), but one can still clearly detect more than 15 lines.

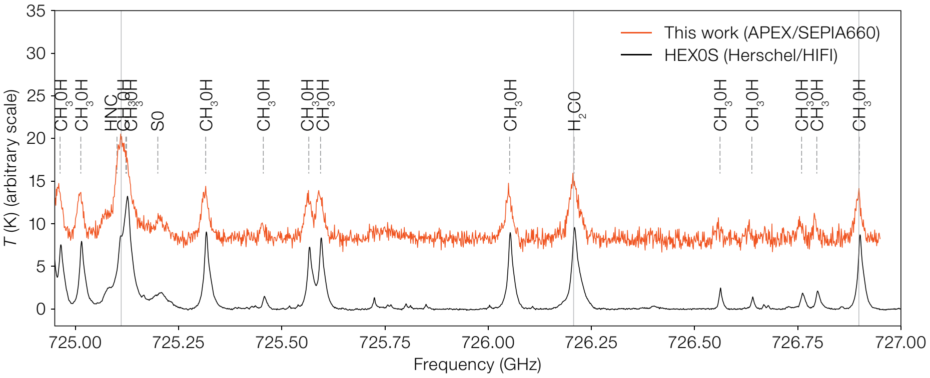

Figure 4. Selected portion of the SEPIA660 spectrum (in red) not covered by the CSO data. Labels have been added to detected lines. The HEXOS spectrum from Herschel/HIFI is also shown for comparison (in black). Note that the temperature scale is arbitrary, and an offset between the spectra has been introduced to enable comparison.

While this portion of the spectrum is not covered by the CSO dataset, it can be compared with the Herschel-HIFI observations from the HEXOS Key Program[b]. To compare our data, we need to keep in mind the different spatial resolutions of Herschel and APEX. At this frequency the Herschel beam size is ~ 30 arcseconds, i.e., an area that is about 11 times bigger than the APEX beam. The Herschel spectrum therefore contains emission from several distinct spatial and velocity components[c], namely the “hot core”, the “compact ridge”, the “plateau” and the “extended ridge”; all with slightly different line widths and different velocities relative to the local standard of rest, v_{lsr}.

The HIFI spectrum is also shown in Figure 4 (in black). The noise level is much smaller (~ 30 mK) in the Herschel data, but with only 60 seconds integration and a very low atmospheric transmission, SEPIA660 can detect the most prominent features. Long vertical lines mark the peak intensities of three selected line profiles (HNC, H_2CO and (CH_3OH) and different velocity offsets are visible between the two spectra at these transitions, each of them tracing different gas components.

The relatively short observations toward Orion-KL presented here demonstrate the capabilities of SEPIA660 in its extended tuning range, a range not available in the previous incarnation of the instrument, and somewhat beyond the ALMA specifications. Even with the very low atmospheric transmission available in this frequency range, we can detect more than 100 strong lines in this archetypical star-forming region. The good sideband rejection ratio ensures very little contamination between sidebands and makes this instrument ideal for molecular line surveys and for studying the chemistry of the interstellar medium in our Galaxy.

Acknowledgements

We thank P. Schilke for kindly providing the CSO spectrum displayed in Figure 4. This work was supported by the Chilean CONICYT astronomy programme, ALMA-CONICYT funds, ALMA Support Astronomer Position (Project No. 31AS002).

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Links

[1] APEX webpage: http://www.apex-telescope.org
[2] The GARD team website: https://www.chalmers.se/en/departments/see/research/OSO/gard
[3] The Call for SEPIA660 Science Verification: https://www.eso.org/sci/activities/apexsv/sepia/sepia-band-9.html

Notes

[a] APEX is a collaboration between the MPIfR, OSO, and ESO, with Chile as the host country.
[b] The HEXOS Orion-KL spectrum was obtained through the NASA Infrared Processing and Analysis Center (IPAC) Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.
[c] See Crockett et al. (2014) for a detailed description of the different Orion-KL components.

ESO/M. Alexander

APEX is situated on the Chajnantor plain at 5000 metres altitude.

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Peering through SPHERE Images: A Glance at Contrast Limitations

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Various structures are visible within Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) images that are not always straightforward to interpret. In this article we present a review of these features and demonstrate their origin using simulations. We also identify which expected or unexpected features are limiting the contrast reached by the instrument and how they may be tackled. This vision paves the way to designing a future upgrade of the SPHERE instrument and the next generation of high-contrast instruments such as those planned for the Extremely Large Telescope (ELT).

Imaging exoplanet and circumstellar discs with SPHERE

Direct imaging provides key information for understanding the nature of exoplanets, their formation and evolution processes. It is complementary to other detection techniques since (i) it is biased towards distant giant gaseous planets hosted by young stars, (ii) it enables direct extraction of the planet's thermal emission and its spectrum and (iii) it reveals the planet in its birth environment and its connection to the circumstellar disc's properties. Dedicated instruments have been built worldwide to scrutinise very short separations (below 500 milliarcseconds), and reach very high contrasts (more than 10^{-6}) between the host star and its planetary companions in the near infrared (NIR).

In 2014, the SPHERE instrument was installed on Unit Telescope 3 (Melipal) of the Very Large Telescope (VLT) at the ESO Paranal Observatory (Beuzit et al., 2019). The common path infrastructure of SPHERE is equipped with an extreme adaptive optics (AO) system known as SAXO (Fusco et al., 2006) and coronagraphs (such as the apodised Lyot Coronagraph, APLC; see Carbillet et al., 2011 and Guerri et al., 2011), allowing it to recover the diffraction-limited angular resolution of the 8-metre telescope and to reach a contrast of 10^{-4} at a few hundred milliarcseconds in the raw images. This common path infrastructure feeds three scientific instruments[1]: the InfraRed Dual-band Imager and Spectrograph (IRDIS; Dohlen et al., 2008), the Integral Field Spectrograph (IFS; Claudi et al., 2008) and the Zurich Imaging POLarimeter (ZIMPOL; Schmid et al., 2018).

Since 2014, the SPHERE instrument has delivered a wide variety of astrophysical results and impressive images (including nine ESO press releases[2]). So far, SPHERE has contributed to the discovery of two confirmed exoplanets (HIP65426b, Chauvin et al., 2017; and PDS70b, Keppler et al., 2018) and additional candidates are being followed up with the SpHere INfrared survey for Exoplanets (SHINE; Chauvin et al., 2017) within the Guaranteed Time Observations (GTO). From the current results, a clear paucity of giant planets appears beyond typically 10 astronomical units. Can we improve the current SPHERE limitations to access closer separations and fainter objects?

The unique combination of extreme AO correction and the coronagraph reveals very faint structures in the images that were not always expected. In order to better understand the images delivered by SPHERE and to provide clues about its current limitations, and thus to shed light onto future high-contrast instrumentation pathways, we present and explain the various features visible in the SPHERE images (see Figure 1) by comparing on-sky images to simulations.

To simulate SPHERE images, the following are included: (i) the VLT pupil showing central obstruction and spiders holding the secondary mirror; (ii) von Karman atmospheric turbulence (at seeing ~ 0.85 arcseconds) and its correction by the SAXO AO; (iii) the Apodized Pupil Lyot Coronograph (APLC); (iv) the remaining high-order optical aberrations within SPHERE; and (v) photon and detector noise. The overall light path is schematically presented in Figure 2 (from left to right) where the light is propagated from pupil planes to focal planes by a Fourier transform, under the Fraunhofer far-field approximation. At the entrance of this setup, the SAXO residual phase is simulated using a Fourier-based analytical code (Jolissaint et al., 2006) from which an instantaneous coronagraphic exposure is produced. "Pseudo-long exposures", are obtained by summing 500 temporally uncorrelated exposures.

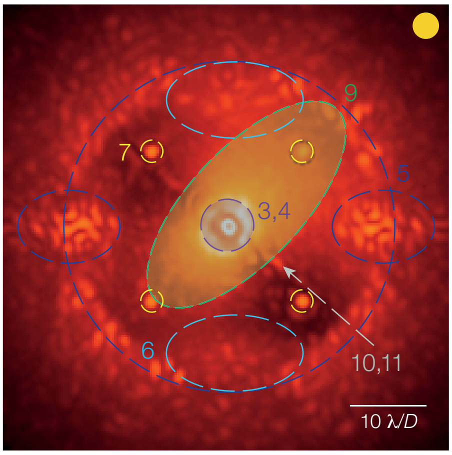


Figure 1. Typical image obtained with the SPHERE-IRDIS instrument (H2 narrow-band filter at 1.6 μm). The various structures are highlighted with numbers referring to the figure(s) in which they are explained. The yellow dot in the top right-hand corner indicates that this is a real on-sky image taken with SPHERE.

The final simulated images have the same spectral response as the SPHERE filters[3], by summing images at different wavelengths over every nanometre. Most of the figures presented here show two simulated images: one using an ideal coronagraph, which perfectly cancels the light diffracted by a fully circular telescope aperture (Sauvage et al., 2010), and which is affected only by residual phase errors from the AO system in addition to the phase term from which the feature originates; the other one using an APLC coronagraph, affected by all of the main phase error terms visible in SPHERE images. The figures illustrating the pupil plane images are shown in blue and the focal plane images are shown in red. A yellow circle in the top right-hand corner indicates real images from SPHERE. All

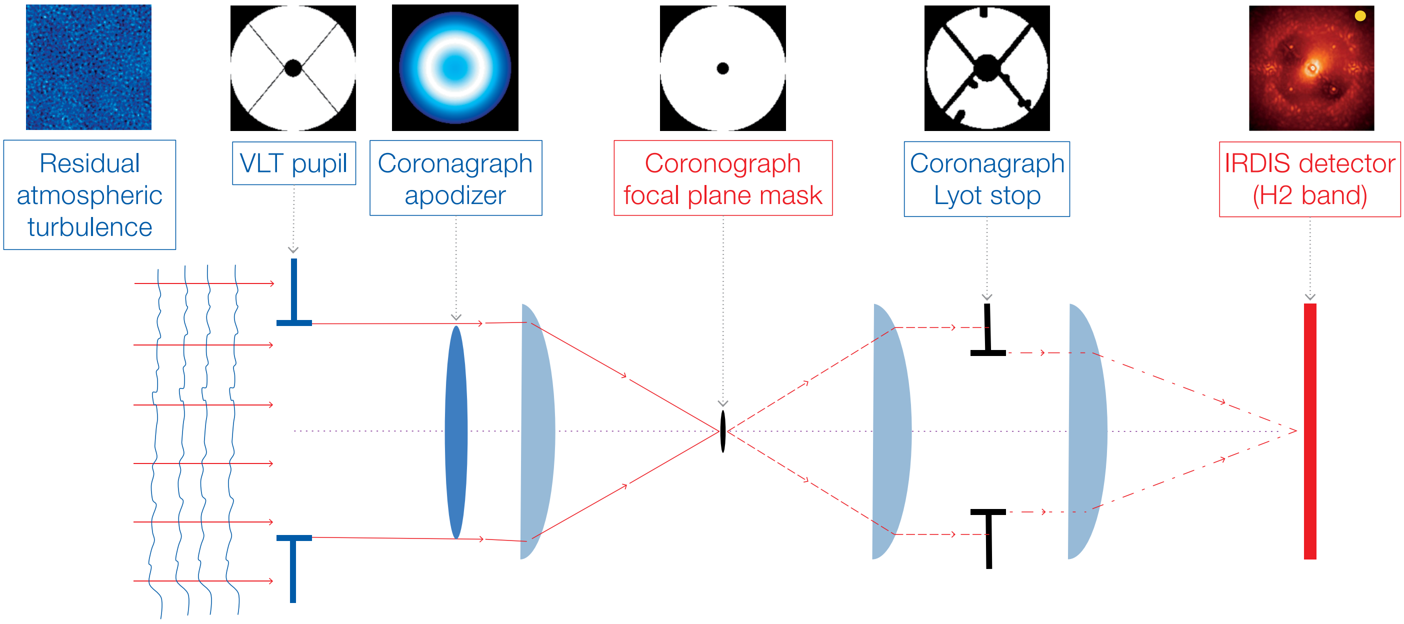


Figure 2. SPHERE-IRDIS APLC coronagraphic setup used to produce the simulations. Phase and amplitude are shown in the pupil planes (blue) and intensity in the detector plane (red).

images are cropped to 200 × 200 pixels (about 2.5 arcseconds).

Dissection of a SPHERE image

The coronagraph is essential to reaching high contrast at close separation from the star. Its role is to suppress as much diffracted light from the star as possible while preserving any other astrophysical signal present in the field of view.

Effect of the coronagraph (Figure 3)

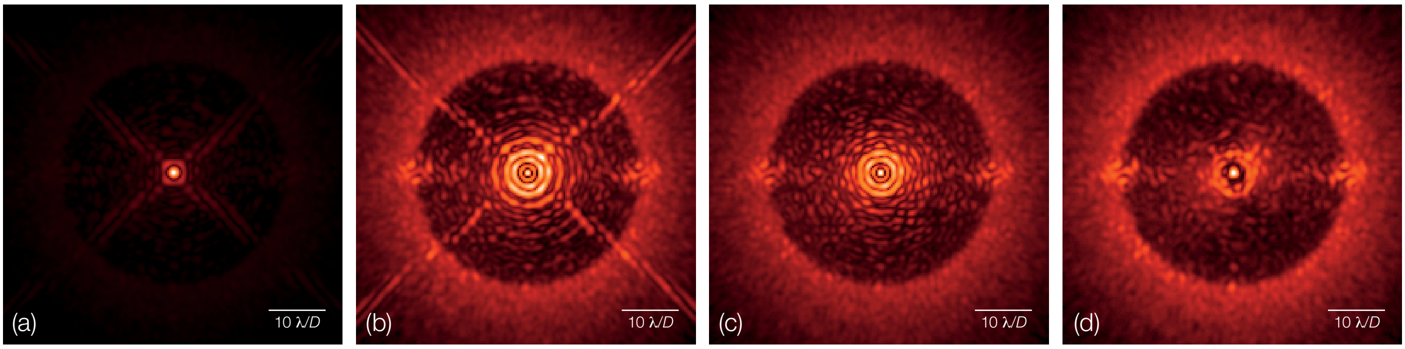
Without a coronagraph, the diffracted light of the central star, i.e., the point spread function (PSF), hides its environment (Figure 3a). It is possible to block the light of the inner core of the PSF by placing an opaque mask in the focal plane before re-imaging the star (Figure 3b). The very central part of the image shows a bright spot where one might naïvely expect a dark spot; this is the so-called Poisson or Arago spot, which is due to diffraction by the coronagraphic focal plane mask.

To remove the diffraction pattern due to the telescope aperture, a Lyot stop is placed in the following pupil plane, consisting of a wider central obstruction, wider spiders and smaller outer diameter (Figure 3c). In order to smooth the sharp edges of the VLT pupil and thus avoid strong diffraction effects (ripples in the focal plane, as in the Gibbs effect), a pupil apodiser is placed upstream of the coronagraph focal plane mask (Figure 3d). Its transmission function has been optimised to avoid these ripples while keeping a high throughput and resolution (Soummer et al., 2005). As a result, under very good conditions SPHERE can reach a contrast of up to 10^{-4} at 250 milliarcseconds in the raw coronagraphic image with a 50% transmission at 100 milliarcseconds in the *H*-band[4].

Effect of the VLT pupil on the coronagraph signature (Figure 4)

The coronagraph design, its resulting performance, and the central image pattern are all driven by the shape of the telescope pupil. From a circular pupil (Figure 4a) to a centrally obscured pupil (Figure 4b), a brighter ring appears close to the star. When the spiders are added

Figure 3. Illustration of the APLC coronagraph effect (*H2*-band): (a) non-coronagraphic image, (b) coronagraphic image with only the focal plane mask, (c) adding the Lyot stop downstream of the focal plane mask, (d) adding the SPHERE pupil apodiser upstream of the focal plane mask.



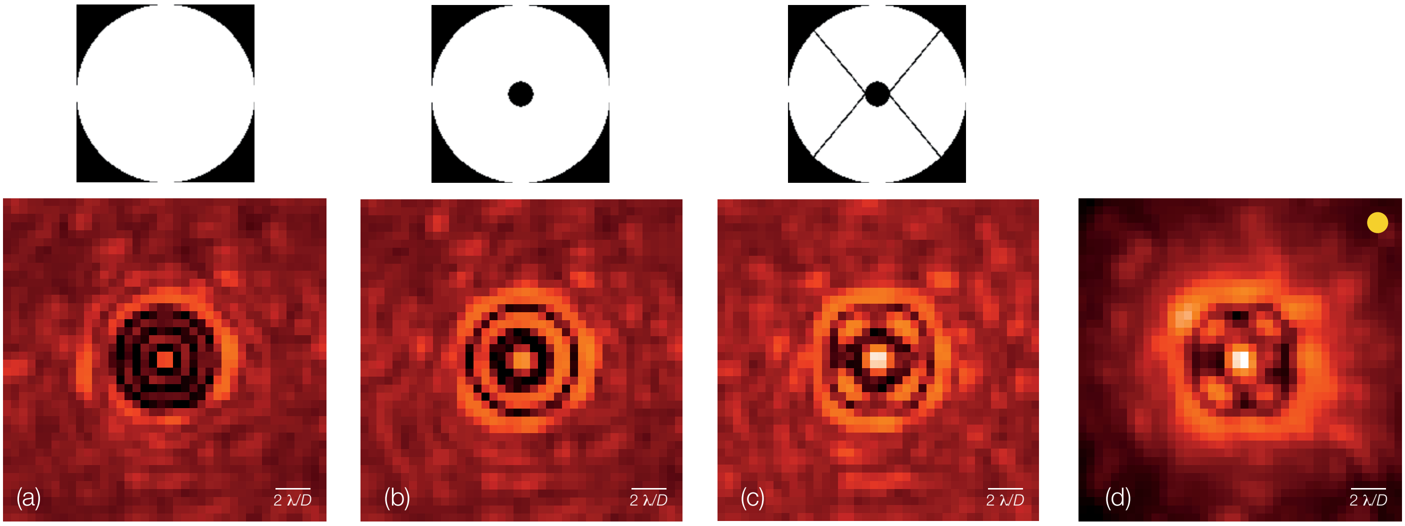


Figure 4. Illustration of the VLT pupil effect on the APLC coronagraphic images (*Y2*-band): (a) full circular aperture, (b) pupil with central obstruction, (c) VLT pupil including spiders and central obstruction and (d) corresponding on-sky SPHERE-IRDIS image.

this bright secondary ring is broken into four petals (Figures 4c and d). These patterns are strongly dependent upon the observing wavelength as the size of the focal plane mask is fixed — Figure 4 shows the specific case of *Y*-band images at 1.02 μm to highlight this effect.

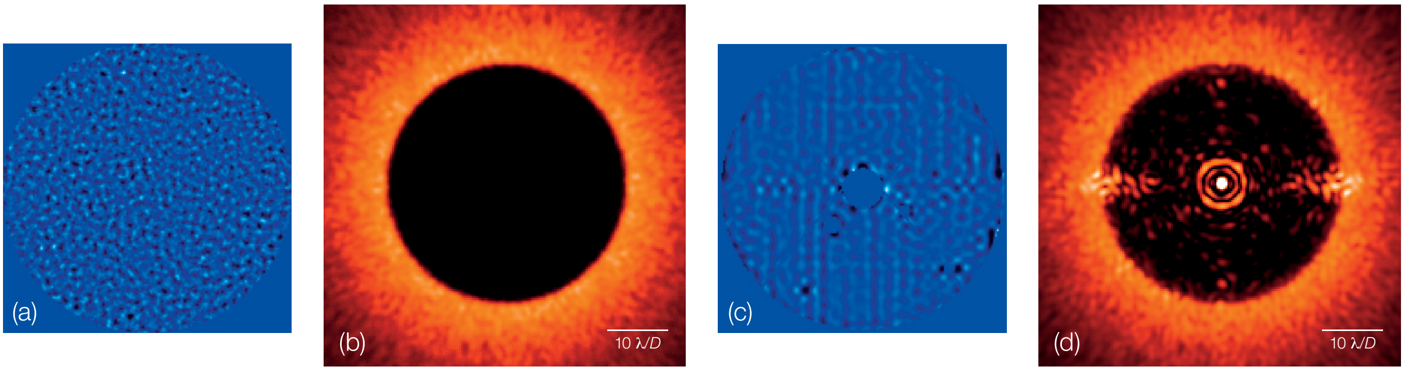
A second type of feature apparent on the images originates from the SAXO system. SAXO is composed of three main elements: (a) a piezo stack high-order deformable mirror (HODM) with 41 actuators across the pupil and a tip-tilt deformable mirror (TTDM) to modulate the incoming phase distorted by the atmospheric turbulence; (b) a Shack-Hartman (SH; Sauvage et al., 2014) wavefront sensor (WFS) to sense the phase of the incoming wavefront at 1380 Hz; and (c) a real time computer to analyse the wavefront and compute the correction command to be sent to the deformable mirrors (DMs) in real time. When the target is faint, the main error comes from the measurement noise. In the following, the target star is considered bright enough (less than 8 magnitudes in the *V*-band) to ignore this error.

The fitting error (Figure 5)

As the number of HODM actuators is finite, only the low frequencies up to the cut-off frequency, defined by the HODM inter-actuator pitch, can be corrected. The simulated AO residual phase including only the fitting error (Figure 5a) shows residuals with a typical size equal to the inter-actuator spacing and smaller. In the focal plane image it creates a central circular dark zone, called the corrected area, delimited by the correction ring (Figure 5b). The seeing-limited region lies outside of this corrected area, where the contrast reached is primarily limited by the seeing conditions.

In SPHERE images, the correction ring shows two bright patterns in the horizontal direction (Figure 1, dark blue) which are due to the imprint of the HODM actuator grid. The HODM is made up of linear arrays of 22 piezostack actuators joined in the middle. We can visualise this HODM grid by using the Zernike sensor for Extremely accurate measurements of Low-level Differential Aberrations (ZELDA; N' Diaye et al., 2013) that is a phase mask placed at the location of the coronagraph FPM converting upstream phase errors into intensity. An example

Figure 5. Illustration of the correction radius due to the fitting error (*H2*-band): (a) AO residual phase with only the fitting error, (b) corresponding ideal coronagraphic image showing a perfect dark hole, (c) the real HODM physical shape is not homogeneous and (d) this results in additional patterns in the image.



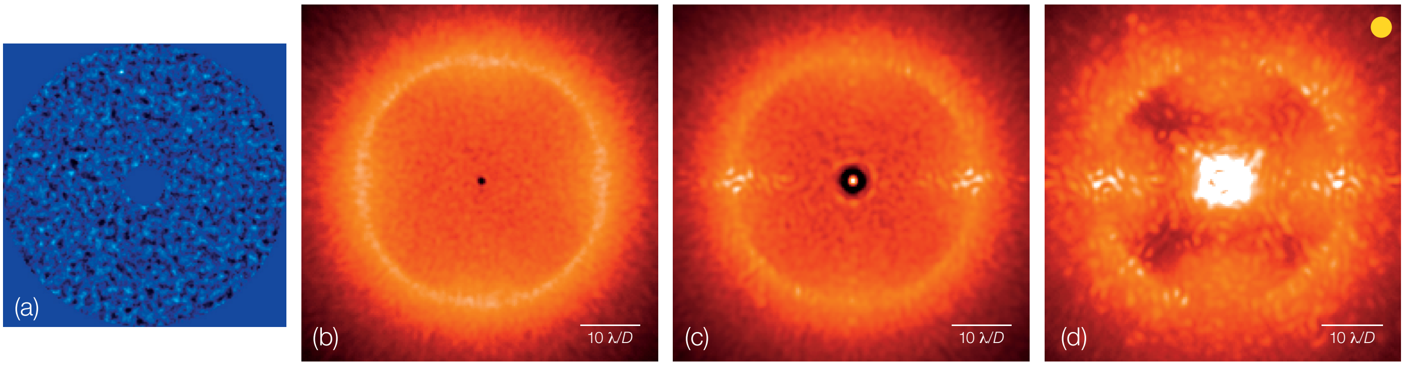


Figure 6. Illustration of the folded light in the corrected zone due to the aliasing error (*H2*-band): (a) AO residual phase showing lower spatial frequencies, (b) simulated ideal coronagraphic image, (c) simulated APLC coronagraphic image and (d) on-sky image where aliasing dominates.

ZELDA image taken on internal source is shown in Figure 5c (Vigan et al., 2018). When propagating this phase, the resulting image shows these patterns (Figure 5d). In order to avoid the light diffracted by defective actuators of the HODM reaching the image, the coronagraph Lyot stop was remanufactured with 6 patches to hide dead actuators (Figure 2).

The aliasing error (Figure 6)

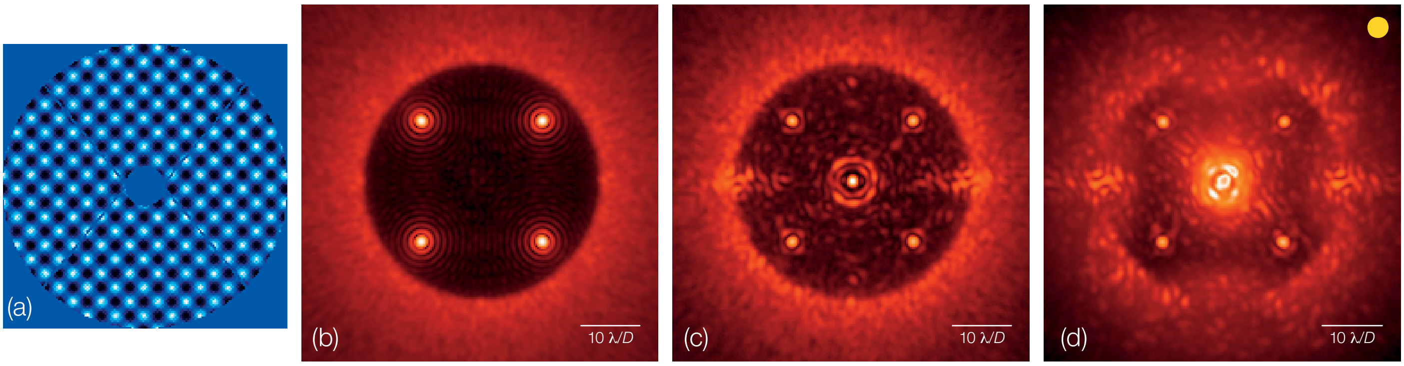
The WFS has limited spatial sampling of the incoming phase and, as a result, the uncorrected high spatial frequencies of the atmospheric turbulence may be seen by the WFS as low spatial frequencies (Figure 6a). The HODM then corrects these frequencies, but since they are not real some light is instead scattered into the corrected area (Figures 6b-d). This aliasing effect is amplified along the WFS sub-aperture directions, giving rise to a typical cross shape along this preferential direction. Moreover the aliasing effect involves spatial frequencies close to the HODM cut-off frequency and therefore the aliasing effect is more intense close to the corrected radius. To bypass this aliasing effect, a field stop (a square hole of variable size) is placed upstream of the SH-WFS to filter out the high frequencies that can neither be analysed nor corrected (Poyneer et al., 2004; Fusco et al., 2014). Depending on the seeing conditions, different filter sizes can be used to minimise aliasing; the smallest filter size can be used under very good observing conditions as this effect increases with the seeing.

The satellite spots (Figure 7)

Sometimes two perpendicular sine waves are applied to the HODM (the so-called "waffle mode", Figure 7a). This pattern creates four satellite spots in the focal plane image. Each spot is a pure copy of the star image and hence shows the same aberrations (Figures 7b and c). The intensity of the satellite spots is given by the sine wave amplitude, their position by the sine wave frequency; their direction is perpendicular to the sine wave direction. Secondary orders create multiple satellite spots in the image, which are usually too faint to be observed in SPHERE images. In addition, owing to the finite spectral bandwidth of SPHERE, the satellite spots are always slightly radially elongated (Figure 7b).

This waffle mode is commonly applied at the beginning of the observing sequence to estimate the location of the centre of the star behind the coronagraph signature in the final image, which is precisely located at the intersection of the four satellite spots. Note that as a result of its manufacturing process, the grid of the HODM creates a similar pattern, provoking the presence of bright spots along the HODM grid direction (horizontally and vertically) located at 40 λ/D in the SPHERE images (λ being the observation wavelength and D the effective telescope diameter).

Figure 7. Illustration of the satellite spots (*H2*-band): (a) waffle pattern applied on the HODM with a frequency of 14 cycles per pupil diameter, (b) simulated ideal coronagraphic image obtained with the waffle pattern added to the AO residual phase resulting in four satellite spots located at 14 λ/D, (c) simulated APLC coronagraphic image and (d) on-sky image taken with the waffle mode.



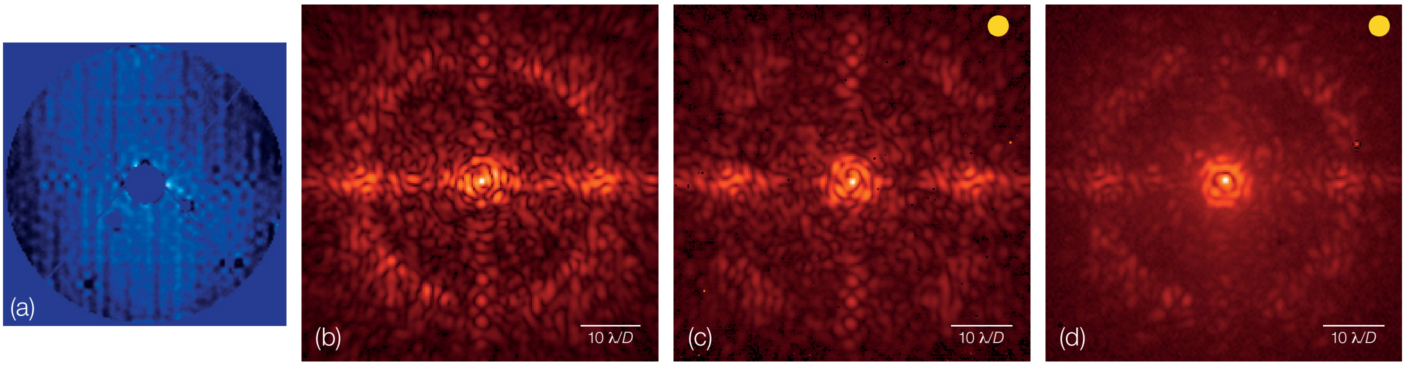


Figure 8. Illustration of the non-common path aberrations (*H2*-band): (a) non-common path aberrations phase map upstream of the coronagraph focal plane mask estimated using the ZELDA mask, (b) simulated APLC coronagraphic image using this estimated ZELDA phase map, (c) internal source image and (d) on-sky image where the non-common path aberrations are dominant.

The contrast killers

In the context of high-contrast imaging with instruments such as SPHERE, two major aspects greatly affect the final contrast performance: (i) the errors that provoke starlight leakage out of the coronagraph; and (ii) the errors that are not temporally stable, or more generally not deterministic, and hence cannot be removed by any current post-processing techniques. In the following we focus on the errors affecting the corrected area in the images, that is to say low-order residual aberrations.

The non-common path aberrations (Figure 8)

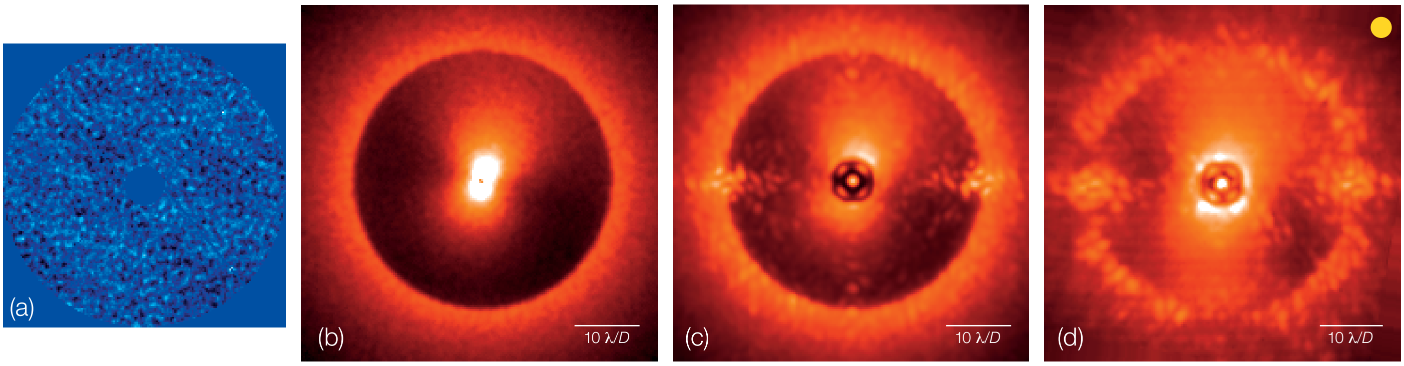
Under very good conditions, current high-contrast images are limited by speckles originating from non-common path aberrations (NCPA). These are aberrations that are sensed and corrected for in the AO arm, but that are not present in the light path of the scientific subsystems and vice-versa. Like the AO residuals, they distort the wavefront so that each incoming light ray interferes with the others in the focal plane to form the "speckle field" (Figure 8b). The size of each speckle is typically that of one resolution element (1 λ/D), as for planetary signals, and their typical contrast can go up to 10^{-4}, whereas that of the sought planetary signals is less than 10^{-6}.

Advanced post-processing techniques are then necessary to detect exoplanet signals. NCPA that are located upstream of the coronagraph focal plane mask have been recently measured thanks to the ZELDA mask on the SPHERE internal source (Figure 8a, Vigan et al., 2018). When comparing the image simulated using this NCPA measurement (Figure 8b) to the internal source image (Figure 8c), a similar speckle field is observed. Under good observing conditions, such a speckle field is indeed limiting the contrast reached in the AO-corrected zone (Figure 8d).

The wind-driven halo (Figure 9)

This halo appears when high wind speeds move the upper level atmospheric turbulence across the pupil considerably faster than the AO loop can correct for. The AO residual phase shows strong atmospheric residuals with a clear directional pattern along the wind direction (Figure 9a). When propagating this phase, it produces a typical butterfly-shaped structure in the focal plane image, along the wind direction (Figures 9b–d). This temporal error significantly affects the contrast reached by the instrument (Mouillet et al., 2018). Recent studies have shown that the fast, high-altitude jet stream atmospheric layer (typically located at about 12 km above Cerro Paranal), whose wind speed can reach 50 m s^{-1}, is the main cause of the wind-driven halo (for example, Madurowicz et al., 2018). Moreover, this halo shows an unexpected asymmetry caused by interference between this temporal lag error and scintillation errors

Figure 9. Illustration of the wind-driven halo due to the Jetstream layer (IFS, *Y*-band): (a) AO residual phase map showing large atmospheric residuals as ripples perpendicular to the wind direction, (b) simulated ideal coronagraphic image using only this phase map, (c) simulated APLC coronagraphic image and (d) on-sky image where the wind-driven halo dominates.



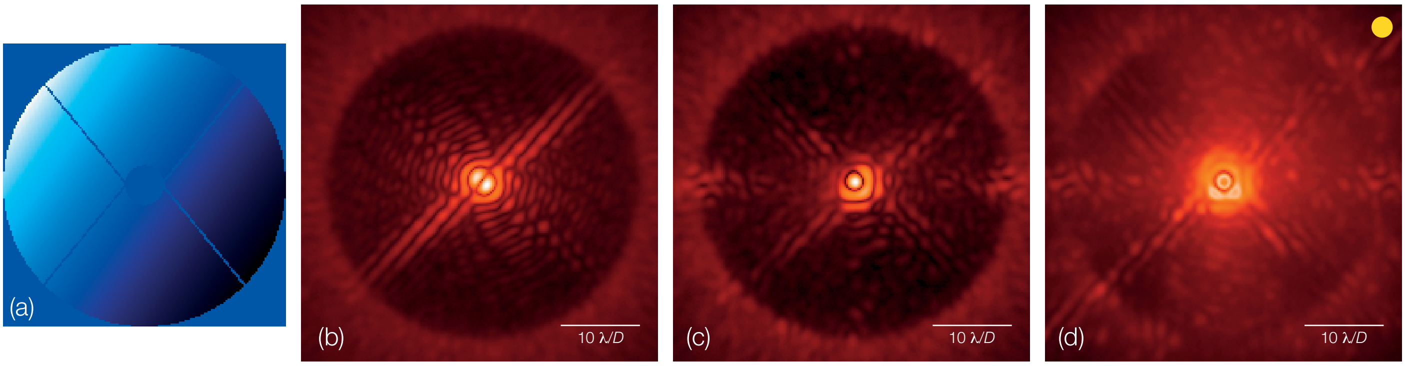


Figure 10. Illustration of the low order residuals (*K1*-band): (a) Tilt phase map added to the AO residual phase, (b) simulated ideal coronagraphic image with only tilt error added to the AO residuals, (c) simulated APLC coronagraphic image and (d) on-sky image where LORs dominate.

whose effect is also stronger with higher-altitude turbulence (Cantalloube et al., 2018).

Low-order residuals (Figure 10)

Tip-tilt errors (Figure 10a) create image jitter. Consequently, the PSF core is not correctly centred behind the coronagraph focal plane mask. In addition, the diffraction patterns from the pupil and the spiders are not entirely hidden by the Lyot stop (Figures 10b and 10c). Fast low-order residuals may arise from residual atmospheric turbulence and telescope vibrations, while atmospheric dispersion residuals and differential thermo-mechanical effects cause slow low-order residuals.

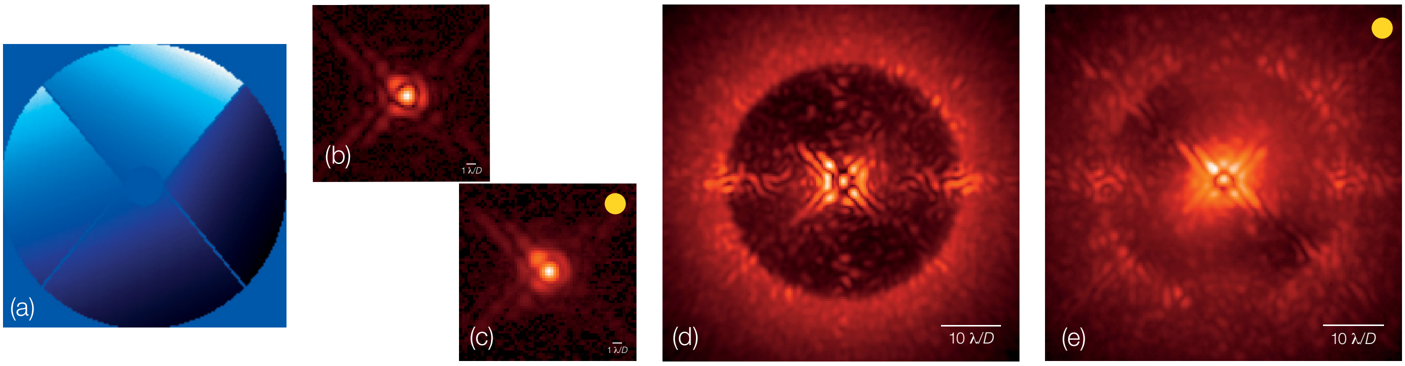
In SPHERE, these slow residuals are minimised by a differential tip-tilt sensor (Baudoz et al., 2010). This differential tip-tilt sensor uses 2% of the infrared light at the observing wavelength, picked-off just before the coronagraph focal plane mask, to estimate the position of the PSF core every second; that is then centred by the tip-tilt mirror of SPHERE. When the target star is faint (around 8 magnitudes in *H*-band) the integration time on the differential tip-tilt sensor is longer, which potentially causes stronger low-order residuals. Also, as the size of the focal plane mask is fixed, the effect of the low-order residuals in the final image is stronger when the observing wavelength increases (Figure 10d).

The low wind effect (Figure 11)

During the night, the M2 spiders can cool below the ambient air temperature by radiative losses as their emissivity is significantly higher than that of air. As a consequence, under low wind conditions, a layer of colder air — which therefore has higher refractive index — forms around the spider (Sauvage et al., 2015). When the windspeed is high, the dense air is blown away, but when the wind is slow, an abrupt change of air index is seen from one side of the spider to the other. As a result, and since the SH-WFS is insensitive to such a phase step, each quarter (or fragment) of the pupil shows a different piston, and sometimes tip-tilt phase error (Figure 11a). The corresponding PSF shape is modified, often appearing with two bright side lobes surrounding the central PSF core, and hence this is unofficially referred to as the “Mickey Mouse effect“. Since the starlight is no longer concentrated in the central core (Figures 11b and 11c), this results in strong starlight leakage off the coronagraph focal plane mask (Figure 11d). This effect is always present to some degree and becomes dominant when the wind speed is too slow to reduce the temperature difference between the spiders and the ambient air (Figure 11e).

To mitigate the low wind effect at the VLT, the M2 spiders were covered with a low-emissivity coating, thus preventing strong radiative cooling. This solution has proven effective, reducing the occurrence of this effect from 18% to 3% (Milli et al., 2018).

Figure 11. Illustration of the low wind effect (*H2*-band): (a) Differential tip-tilt phase map due to low wind effect, (b) simulated non-coronagraphic PSF, (c) corresponding on-sky image of the non-coronagraphic PSF, (d) simulated APLC coronagraphic image including the differential tip-tilt phase map and (e) on-sky image where the low wind effect dominates.



Towards the future generation of High Contrast Imaging (HCI) instruments

Going from the first generation of exoplanet imagers, such as the Nasmyth Adaptive Optics System – Near-Infrared Imager and Spectrograph (NaCo) at ESO, to the latest generation of instruments, such as SPHERE, the contrast reached increased by an order of magnitude. This gain also revealed all the instrumental structures that are presented in this article. Analysing the origin, behaviour and effects of these structures on the current contrast performance of SPHERE offers a better understanding of high-contrast instruments. It also adds clear constraints to lead the design of future high-contrast imagers and specifically ELT instruments equipped with a high-contrast mode. Based on these considerations, SPHERE has demonstrated that scintillation, pupil fragmentation, AO temporal errors, and NCPA must be specifically tackled in the future.

In order to gain sensitivity, especially at closer separations to the star, the next generation of high-contrast instruments can build on these different aspects. For instance, on the AO side, by using a WFS less sensitive to aliasing and noise measurement (such as a Pyramid WFS; Ragazzoni et al., 1999), a faster AO loop (for example, more efficient real time computer architecture and predictive control) and going with a faster, hence more sensitive, detector and a fast deformable mirror. On the coronagraph side, by designing a coronagraph that is achromatic and less sensitive to low-order residuals (for example, pupil plane coronagraph) and offers a smaller inner working angle. On the instrument itself, correcting for the NCPA by estimating them during the observing run and by applying offsets to the HODM or by applying advanced post-processing techniques.

For ELT instruments, these different aspects will be greatly affected by the design of the telescope itself. The AO system and coronagraph will have to deal with a larger central obstruction, thicker spiders and a segmented primary mirror potentially having co-phasing errors, differential transmission and missing segments. Stay tuned for the ESO Messenger 2025 edition.

Acknowledgements

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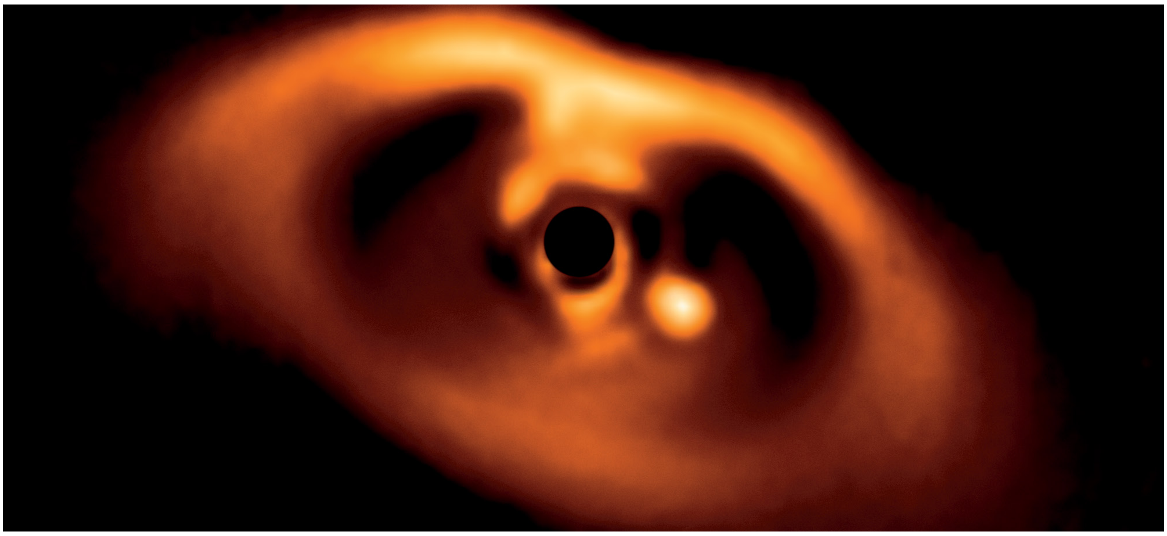
Links

[1] The SPHERE subsystems description can be found at: https://www.eso.org/sci/facilities/paranal/instruments/sphere.html

[2] The SPHERE-related press releases can be found at: https://www.eso.org/public/news/archive/search/?published_until_year=0&published_until_day=0&description=&title=&instruments=57&subject_name=&published_since_day=0&published_since_month=0&published_until_month=0&id=&published_since_year=0

[3] SPHERE filters description and transmission curves: http://www.eso.org/sci/facilities/paranal/instruments/sphere/inst/filters.html

[4] SPHERE user manual: https://www.eso.org/sci/facilities/paranal/instruments/sphere/doc/VLT-MAN-SPH-14690-0430_v100_p2.pdf



ESO/A. Müller et al.

This SPHERE image of the protoplanetary disc around the young star PDS 70 reveals a planet in the act of formation.

Astronomical Science

EHT Collaboration

The Event Horizon Telescope leveraged a global network of radio facilities, including ALMA and APEX, to reveal the first image of the shadow of a black hole. The black hole in M87 is approximately 6.5 billion solar masses.

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KLASS – The Role of Low-Mass Galaxies from Cosmic Dawn to Cosmic Noon

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The KMOS Lens-Amplified Spectroscopic Survey (KLASS) is an ESO Large Programme that uses the KMOS infrared spectrograph to investigate the role of low-mass galaxies at several epochs of cosmic time. KLASS has targeted galaxies behind massive clusters, using gravitational amplification and stretching to observe galaxies that are intrinsically very faint. By pushing KMOS to the limits of its capabilities, we have obtained new constraints on the timescale of the reionisation process, finding that the intergalactic medium was almost completely neutral at a redshift of around 8, and that turbulence plays a major role in shaping low mass galaxies at intermediate redshifts (0.5 < z < 2).

In the first billion years of the Universe's life — the Cosmic Dawn — low-mass galaxies were the dominant population and their stellar emission was dominated by massive, short-lived, bright stars. Ultraviolet photons created by these stars were likely responsible for the most important transition that the Universe underwent after recombination: the reionisation of the intergalactic medium (IGM). The bulk of this process occurred at redshifts $z > 7$, and coverage of this parameter space by spectroscopic surveys is still sparse and incomplete.

At lower redshifts ($0.5 < z < 2$), low-mass galaxies played a significant role in the evolution of the global star formation rate density, and they eventually contributed to the growth of more massive galaxies by merging processes. Feedback processes are much more effective in low-mass galaxies, as the energy release from supernovae and other feedback sources can exceed the gravitational binding energy. We thus expect the dynamical, morphological, dust and metallicity evolution in low-mass galaxies to be significantly different compared to their more massive siblings.

KLASS scientific goals

KLASS is designed to exploit the magnification due to gravitational lensing by massive clusters to observe (background) sources that are intrinsically much fainter than objects we can observe in ordinary fields; the image stretching in angular extent increases the spatial resolution. Our targets are galaxies that are gravitationally lensed by six massive galaxy clusters, four of which are among the well-known Frontier Fields[1]. These are clusters that were previously observed by the large Hubble Space Telescope (HST) grism programme called the Grism Lens-Amplified Survey from Space (GLASS), which was led by Tomasso Treu. GLASS observed ten clusters with a wide set of spectroscopic observations. Capitalising on the magnification of background sources we were able to explore a range of redshifts and intrinsic magnitudes at a superior depth and quality than in blank fields located near the clusters — an exciting preview of JWST- and ELT-class science.

We have focused on two main scientific goals that are well-suited to the number of targets we can identify behind each cluster and to the number of integral field units (IFUs) in the *K*-band Multi-Object Spectrograph (KMOS):

1. To investigate Lyman alpha (Lyα) emission from star-forming galaxies at redshifts $z > 7$ independently of HST spectroscopic observations, providing validation and cross-calibration of HST results and enabling us to constrain the timeline of reionisation.
2. To probe the internal kinematics of galaxies at $z \sim 1–3$ with superior spatial resolution compared to surveys in blank fields.

KLASS observations were carried out by KMOS in the *YJ* bands (1–1.35 μm). The spectral resolution $R \sim 3400$ is sufficient to distinguish Lyα from potential low-redshift contaminants with the [OII] λ3726, 3729 emission doublet at $z \sim 2$.

Observations were carried out in Service Mode and executed in one-hour observing blocks with repeating A-B-A integration corresponding to science-sky-science observations. Each observing block comprised 1800 s of science integration, and 900 s on sky. Exposure times ranged between approximately 6.5 and 15 hours per target. Dither shifts were included, shifting the pointing between science frames. A star was observed in one IFU in every observing block to monitor the point spread function (PSF) and the accuracy of dither offsets. The PSF was well-described by a circular Gaussian and the median seeing of our observations was 0.6 arcseconds.

Reaching the limits of KMOS: optimising the pipeline

To reach the ambitious goals of the KLASS survey it was necessary to squeeze the most out of our data. Observations of faint Lyα emission, comprising half of our sample, are challenging. The main difficulties that we have had to overcome are:

1. high-redshift candidates are not detected in the continuum with KMOS, so we cannot rely on a robust identification of their position in the spaxel space;
2. we need to subtract the background reliably to reach Poisson sensitivity limits;
3. we need to identify subtle systematics that can lead to spurious identifications of faint lines;
4. we need to quantify exactly the signal-to-noise ratio (S/N) achieved for each pixel of the extracted spectra in order

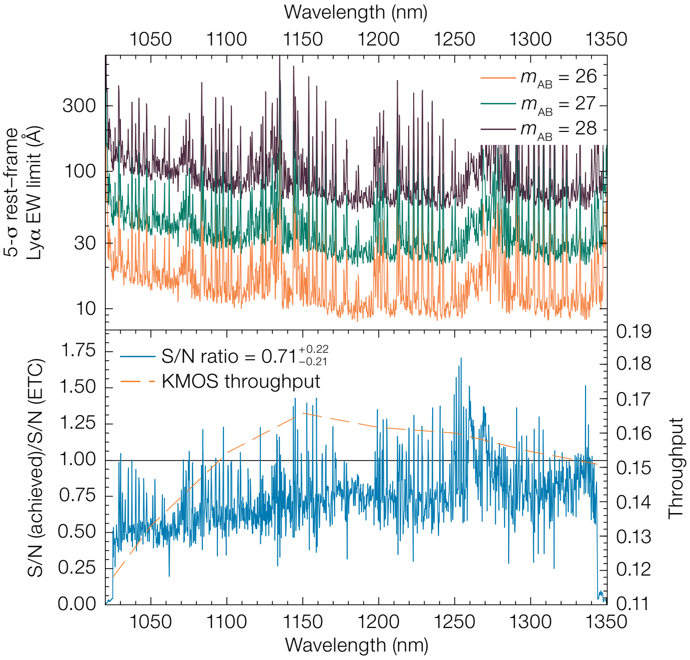

Figure 1. Upper: 5-σ rest-frame equivalent width limits in Lyα as a function of wavelength for three values of the apparent magnitude *m* in the ultraviolet. Lower: Comparison of the achieved sensitivity as a function of wavelength in our deepest exposure with the KMOS exposure time calculator using the same exposure times.

to evaluate the significance of faint lines or to statistically analyse the significance of non-detections, as described below.

To reach our goals we have extensively tailored, optimised and characterised the ESO pipeline (v1.4.3). Details of these improvements are given in Mason et al. (2019), to which we refer the reader. An example of the outcome of our efforts is given in Figure 1 (upper panel), in which we show the effective 5-σ rest-frame equivalent width (EW) limits in Lyα as a function of wavelength for three values of apparent magnitude in the ultraviolet, assuming emission lines are spatially unresolved. It is clear that the sensitivity changes dramatically with variability in the sky emission lines, ubiquitous in the near-infrared, and their effect needs to be factored into the estimate of the survey efficiency.

Another important lesson that we have learned from this exercise is shown in the lower panel of Figure 1, where we compare the observed S/N with that predicted by the ESO exposure time calculator (ETC). We find that, owing to inevitable systematics in sky subtraction, the predicted S/N was about 1.5 times higher than that observed. Future observers are strongly advised to include this factor in their predictions.

Armed with this careful characterisation of the instrument, we have used our data to explore two hot topics in modern cosmology.

Cosmic dawn: which sources reionised the early Universe?

The reionisation of intergalactic hydrogen in the Universe's first billion years is likely linked to the formation of the first stars and galaxies, considered to be the primary producers of hydrogen-ionising photons. Accurately measuring the timeline of reionisation enables us to constrain the properties of these first sources.

Whilst young star-forming galaxies show Lyα emission (121.6 nm) in increasing abundance at higher redshifts up to $z \sim 6$, the fraction of galaxies detected with Lyα emission, and the equivalent width distribution of that emission, decreases rapidly (for example, Fontana et al., 2010; Pentericci et al., 2018 and references therein). This rapid decline of detected Lyα emission is unlikely to be due to the physical evolution of the galaxy properties, as we expect the trend toward stronger Lyα to continue at higher redshifts because of decreasing metallicity and dust content. The decline is most plausibly due to absorption in an increasingly neutral IGM, which progressively absorbs the intrinsic Lyα emission. The drop in the Lyα EW distribution at $z \sim 7$ yields the best current constraint on the mid-stages of the reionisation process (Mason et al., 2018).

By targeting galaxy candidates at $z \sim 8$, KLASS had the explicit aim of extending this analysis to higher redshifts, in order to trace the reionisation process at its peak, when newborn galaxies were producing sufficient ultraviolet photons to significantly ionise the IGM. The choice of an IFU instrument for high-redshift Lyα observations was motivated by indications that ground-based slit spectroscopy measures lower Lyα flux than HST slitless grism spectroscopy. As demonstrated by recent MUSE observations, Lyα emission can be spatially extended and/or offset from the ultraviolet continuum emission, making it likely that slit-based spectroscopy is not capturing the full Lyα flux. Hence, the observed decline in Lyα emission at $z > 6$ could be partially due to redshift-dependent slit-losses as well as reionisation.

The answer from KLASS is unambiguous: despite the high quality of the parent photometric sample based on the best HST images and the depth reached by the KMOS observations, none of the 29 galaxies with photometric redshifts of ~ 8 show significant Lyα emission. Crucially, our sample is composed of a sizeable fraction of intrinsically faint galaxies (thanks to the effect of gravitational lensing), which are most likely to have strong Lyα emission at lower redshifts.

Using sensitivity estimates as a function of wavelength for every target, we have defined a robust Bayesian scheme to derive the neutral hydrogen fraction of the IGM at $z \sim 8$. Our inference accounts for wavelength sensitivity, the incomplete redshift coverage of our observations, the photometric redshift probability distribution of each target, and the patchy nature of reionisation. The KLASS observations enable us to place the first robust lower limit on the average IGM neutral hydrogen fraction at $z \sim 8$ of > 0.76 (with 68% confidence), > 0.46 (95% confidence), providing crucial evidence of rapid reionisation at $z \sim 6$–8. This is shown in Figure 2, in which we compare the derived IGM neutral fraction from KLASS with other constraints. We find that the fraction that we derive is consistent with reionisation history models that extend the galaxy luminosity function to $M_{UV} \lesssim -12$, with low ionising photon escape fractions, $f_{esc} \lesssim 15\%$.

We note that the lack of detected Lyα lines is not (only) due to the difficulty of performing efficient near-infrared spectroscopy. As a counter example, we have detected a faint C IV emission doublet from a known $z = 6.11$ galaxy, that we use to showcase the capability of KMOS to detect very faint emission lines. The resulting spectrum is shown in Figure 3. The emission lines are partly absorbed by a nearby sky emission line and have a total flux of the order of 10^{-17} erg s^{-1} cm^{-2}.

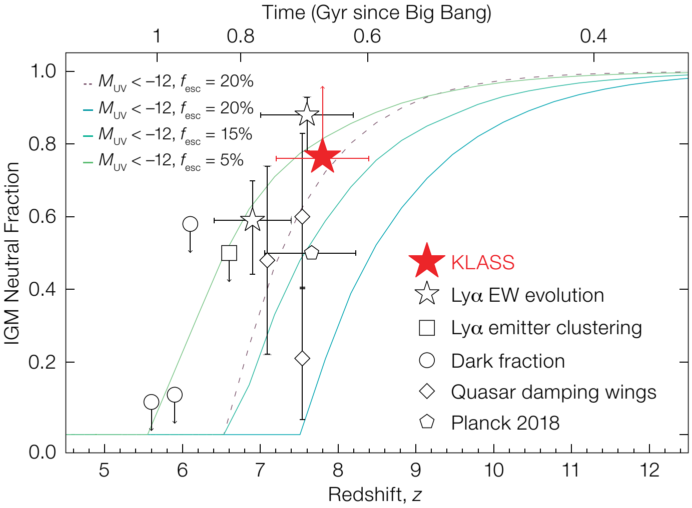

Figure 2. The evolution in redshift of the volume-averaged neutral hydrogen fraction of the IGM. The lower limit from KLASS is the highest-redshift star (shown in red).

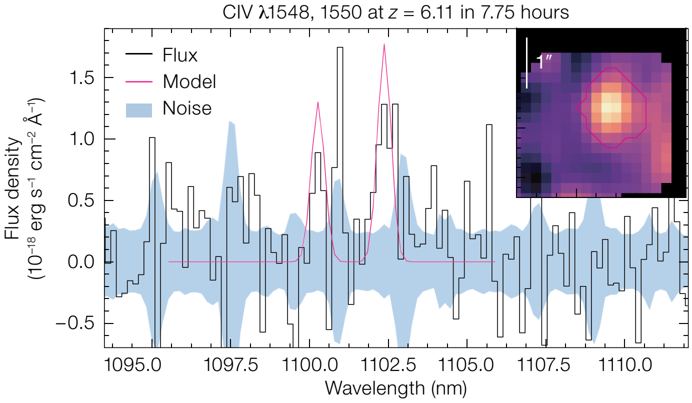

Figure 3. KMOS KLASS 1D spectrum and 2D emission-line map of the galaxy at z = 6.11, centred on the faint C IV doublet emission (in pink).

Cosmic high noon: the dynamical state of low-mass galaxies.

The redshift range $1 < z < 3$ was the most active time in the Universe's history, covering the peak of cosmic star formation history when more than half of the stellar mass in the Universe was built up. Many galaxies at this epoch appear morphologically disordered; the clear bimodality in the galaxy population in the local Universe, between rotating discs and dispersion-dominated elliptical galaxies has not yet been established. How this bimodality arises and which processes change galaxies from discs to ellipticals are still open questions.

Using integral field spectroscopy, we can ask questions about how galaxy morphologies and kinematics are related to their past and ongoing star formation (for example, Förster Schreiber et al., 2009). A key question is whether the increase in star formation rates (SFRs) is driven solely by an increase in density and smooth gas accretion rates at higher redshifts producing steady in-situ star formation, or by more stochastic processes leading to gas infall such as major mergers.

The first generations of integral-field surveys using single IFU instruments (primarily SINFONI and GIRAFFE) as well as recent surveys using KMOS (for example, KMOS^{3D}, Wisnioski et al., 2015) have primarily targeted star-forming galaxies at the high mass end of the galaxy stellar mass function ($\gtrsim 10^{10}$ $M_{\odot}$). Most surveys found samples of $z \sim 1$–3 galaxies which were roughly equally separated into three kinematic classifications: rotation-dominated systems, dispersion-dominated systems and merging/morphologically unstable systems. A key result was that the rotation-dominated systems had systematically higher velocity dispersions than local discs, suggesting that high redshift discs are highly turbulent.

However, there is no clear picture of the kinematic evolution of low-mass galaxies. It is also known that seeing-limited observations can lead to the misclassification of these objects, the result of seeing-induced smearing of irregular rotational features in the spectra.

While adaptive-optics assisted observations are difficult and limited to small samples, the combination of HST imaging, the amplification and size stretching due to gravitational lensing, and the multiplexing capability of KMOS makes it possible to study the internal motions of galaxies with low stellar masses in sizeable samples, and at higher spatial resolution than natural seeing (see Girard et al., 2018 for another example). This was the primary goal of the KLASS observations of intermediate-redshift galaxies.

In the KLASS survey we have observed 50 faint galaxies, spanning the mass range $7.7 < \log (M/M_{\odot}) < 10.8$. Observed redshifts span the range $0.6 < z < 2.3$, with 14 sources at $z > 1.5$ and two at $z > 2$.

For 42 of these galaxies we are able to obtain high-S/N kinematic maps. Some examples are shown in Figure 4, where we show the HST images, the 2D emis-

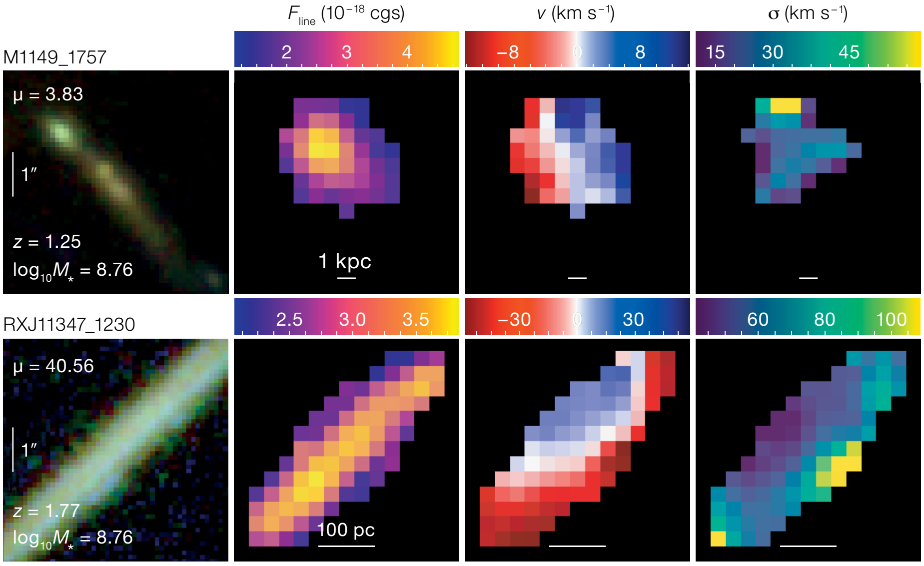

Figure 4. The HST *RGB* composite images, 2D emission-line spectra and velocity maps for two low-mass galaxies in KLASS.

sion lines and the velocity maps (circular velocity and dispersion) for the lowest-mass galaxies in the sample.

The circular velocity v and the velocity dispersion σ are used to classify galaxies as “rotationally supported” when $v/\sigma > 1$. Large values of $v/\sigma > 3$–5 typically indicate “regular rotation”, while lower values indicate that the systems are dynamically hotter, with turbulence in the disc being significantly higher than in local discs.

We find that the majority (77%) of our kinematically resolved sample are rotationally supported, but about a half of the sample (16/34) show particularly low values of $v/\sigma < 3$, meaning that most of the rotation-dominated galaxies are only marginally stable, at odds with what we see in the local Universe. We also find a mean dispersion of $\sigma \sim 55$ km s^{-1} in the sample, similar to previous surveys at the same redshifts.

We also used the observed emission lines in KMOS (Hα at $z < 1$, Hβ at $1 \leq z < 1.8$ or [OII] at $z \geq 1.8$) to estimate the ongoing SFR in our sample, and investigated correlations between rotational state, SFR and stellar mass. Results are shown in Figure 5, where we show how objects with different rotational classifications are located in the main sequence plane. While there is significant scatter, there is some evidence that merging and irregular systems have a relatively large ratio of SFR:M_* (> 0.1 Gyr^{-1}) suggesting that their disturbed gas dynamics may be enhancing star formation (or vice versa) in some of these objects compared to kinematically ordered systems. We also find a strong correlation between the dispersion and the stellar mass and SFR, meaning that high dispersion could be due to stellar feedback in these galaxies. Full results are given in Mason et al. (2017) and Girard et al. (in preparation).

This indicates that turbulence in discs is significantly higher at cosmic noon compared to local discs and thus that the fraction of dynamically hot discs changes with cosmic time. Clearly, turbulence plays a major role in the settlement of rotating discs at low masses in the young Universe.

The power of KMOS has revealed once more the crucial role that faint, low-mass galaxies have had in the history of the Universe. They produced most of the ultraviolet photons required to reionise the Universe in the redshift range $z = 6$–9. They continued to develop during the peak of cosmic star-formation history, building stars in highly turbulent systems. The kinematic analysis of our full sample, which is under way at the moment, will help to complete the picture regarding these fascinating systems.

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Links

[1] HST Frontier Fields: http://www.stsci.edu/hst/campaigns/frontier-fields/

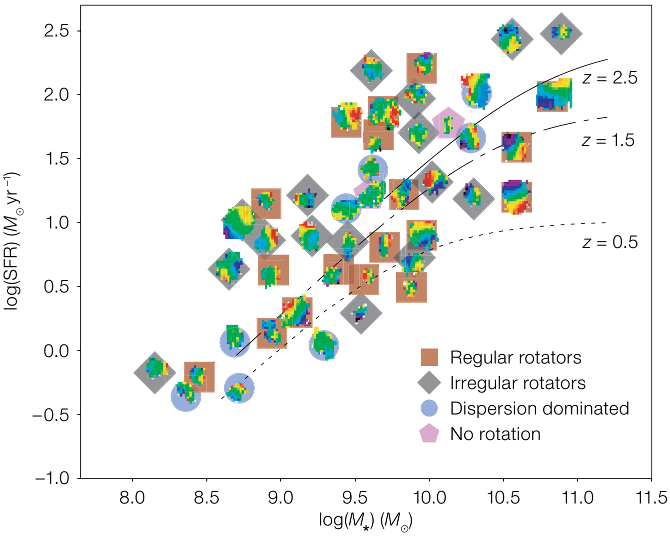

Figure 5. The velocity maps for galaxies in our sample with resolved kinematics, plotted at the galaxy's position on the SFR–M_* plane.

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ALMA Resolves the Stellar Birth Explosions in Distant Radio-Loud Quasars

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Far-infrared photometry with the Herschel Space Observatory has found many examples of ultra-luminous dust emission at around 40 K in the host galaxies of high-redshift, radio-loud 3C Active Galactic Nuclei (AGN). The dust heating could have its origin in the central black hole activity or extreme circumnuclear starbursts, or both. We have used the Atacama Large Millimeter/submillimeter Array (ALMA) in Cycle 3 to study the dust morphology on the kiloparsec scale in a sample of these AGN, and present the results for three well-known distant quasars: 3C298, 3C318, and 3C454. After correction for the non-thermal radiation at 1 mm, the observations imply a starburst origin for the cool thermal dust emission, and a symbiotic physical relationship with the AGN-driven radio source.

The starburst-AGN symbiosis in distant 3C radio source hosts

Given the well-known scaling relations between galaxies and their central black holes, galaxies are believed to experience star formation, i.e., converting gas into stars, and central black hole growth, specifically AGN phenomena, symbiotically. This symbiosis is indeed seen in observations; nearby quasi-stellar objects (QSOs), for instance, prefer blue host galaxies (Trump et al., 2013). The symbiosis of black hole and global galaxy growth is even more intriguing because of the possible feedback effects: positive (AGN-induced star formation), and/or negative (AGN quenching of star formation). Concerning these feedback effects, the class of radio-loud AGN is particularly interesting since these objects — radio galaxies and radio-loud quasars — have radio jets which are known to interact with the host galaxy interstellar medium (ISM). The physical AGN–star formation interplay is an issue of great interest: where, when and how does it occur? To answer these questions, it is necessary to zoom in on the star formation processes in the host galaxies of radio-loud AGN and to conduct a spatial and/or kinematic study of the astrophysical interconnections.

During the past decade our team has used Spitzer, Chandra, and Herschel to investigate partly obscured AGN and star formation in the ultra-massive hosts of $z > 1$ 3C radio galaxies and quasars (for example, Barthel et al., 2012; Podigachoski et al., 2015, 2016a). These objects have been and will continue to be landmarks in the study of active galaxies through cosmic time. Herschel photometry has shown that about a third of these powerful 3C AGN are in fact radio-loud Ultra Luminous InfraRed Galaxies (ULIRGs) as inferred from their large cool dust masses, suggesting star formation rates (SFRs) of hundreds to over a thousand $M_\odot$ year^{-1}. Key questions focus on the nature of this cool dust and its location; is it widespread in the AGN host galaxy and indeed related to massive starbursts, or is it localised and maybe somehow connected to the active nucleus?

Our Herschel studies have also established the interesting trend that the cool dust luminosity is a function of the AGN age (Podigachoski et al., 2015), in the sense that old AGN — large double-lobed radio sources — are characterised by less dust emission than young ones with compact, sub-galactic-sized radio sources. Within the starburst scenario, this would indicate positive feedback during the young AGN phase and negative feedback during its adult phase, or simply fading of the galaxy growth over time. A similar trend was recently reported for high-redshift radio galaxies (Falkendal et al., 2019).

Zooming in using ALMA 1-millimetre observations

In 2016 ALMA was capable of 0.15-arcsecond resolution imaging at a wavelength of 1 mm, and hence permitted a spatial study of star formation related to cool dust on kiloparsec scales. This high resolution also permits optimal subtraction of the co-spatial non-thermal (synchrotron) 1-millimetre emission, using scaled high-resolution centimetre radio images; this is essential to isolate the thermal emission and address its nature.

ALMA Band 7 (1-millimetre) observations of five, far-infrared (FIR) luminous, $z > 1$ 3C objects — three quasars and two radio galaxies — took place during the summer of 2016, with baselines of up to 1.6 km, and a typical on-source integration time of 15 minutes. Standard CASA pipeline calibration was employed at the European ALMA Regional Centre Node in Leiden, the Netherlands. The resulting beam sizes are typically 0.18 arcseconds, and the final 1-millimetre images reach 1σ noise levels of a few tens of μJy beam^{-1}.

As millimetre radiation from the nucleus of a radio-loud object consists of two parts: the thermal Rayleigh-Jeans tail of the cool (30–40 K) host galaxy dust component, and the synchrotron component of its radio source — the strength of which can be extrapolated from the shape of its centimetre radio spectrum. There is also a third component in the form of free-free radiation, but its magnitude is not significant at the rest-frame wavelength of 0.4 mm (Condon, 1992).

To establish the strength and morphology of the cool dust thermal emission in the quasar hosts, that is its Rayleigh-Jeans tail at 1 mm, we combined our ALMA images with the Karl G. Jansky Very Large Array (VLA) *U*-band (2 cm, 15 GHz) images at matched angular resolution (~ 0.18 arcseconds), subtracting a scaled, aligned version of the latter from the former. Gaia positions of the optical QSOs permitted high-precision astrometric alignment of the images, to within one 0.025-arcsecond pixel. We will describe the analysis of these quasars below; the full sample including the radio galaxies will be discussed in a forthcoming article (and quasar 3C298 was already discussed in Barthel et al., 2018).

Three well-known 3C quasars and their central dust structures

Within our Cycle-3 ALMA project (ADS/JAO.ALMA#2015.1.00754.S), three 3C quasars were observed: 3C298

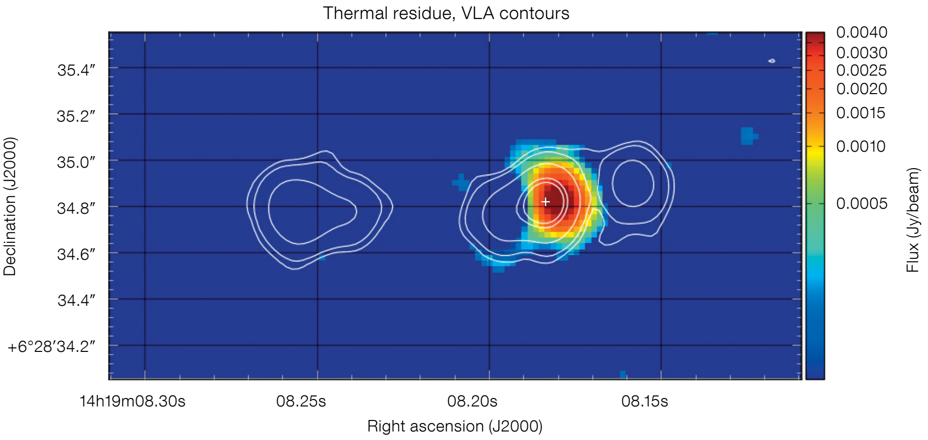


Figure 1. Thermal dust emission at 1 mm in the host galaxy of 3C298, with 2-centimetre radio contours overlaid; the + sign marks the location of the optical QSO.

at $z = 1.439$, 3C318 at $z = 1.574$, and 3C454.0 at $z = 1.757$. Their (projected) radio sizes are, respectively, 14, 10 and 10 kpc, hence they are of sub-galactic dimensions and most likely young. Their model-dependent (see Podigachoski et al., 2015) star formation rates (SFRs), as inferred from their spectral energy distributions (SEDs), are 940, 580 and 620 $M_\odot$ year^{-1}, respectively. Our SED greybody fits to the long-wavelength FIR data predicted thermal 1-millimetre flux densities of 3, 1.5, and 1.5 mJy, for 3C298, 3C318 and 3C454.0, respectively. The ALMA observations were designed to test the SED modelling, specifically to identify or rule out the presence of these massive starbursts, to determine their strength, and to study any astrophysical interconnection with the AGN. The results of this study are discussed separately for each quasar.

3C298 is a compact triple radio source, consisting of a radio core coinciding with the AGN, a western radio lobe 0.4 arcseconds away, and an eastern lobe 1 arcsecond away. The optical QSO is slightly reddened and it displays strong associated CIV absorption from outflowing winds (Anderson et al., 1987). 3C298 is one of the strongest FIR emitters in the 3C catalogue. Its 1-millimetre ALMA image has the triple structure, but the central emission shows evidence of an extended underlying 1-millimetre plateau. We used an accurately aligned, archival VLA 2-centimetre image at comparable resolution to subtract the non-thermal 1-millimetre emission. Since the non-thermal 2-centimetre to 1-millimetre spectral indices for the various source components are unknown *a priori* we used a range of indices (scaling factors) in the subtraction process. Oversubtracting non-thermal centrally peaked emission creates a hole in the central 1-millimetre structure; we conclude that adopting a synchrotron spectral index value of -1 yields the best “organic” thermal 1-millimetre morphology, shown in Figure 1 with the 2-centimetre radio contours overlaid. That structure, having a 1-millimetre flux density of around 3 mJy, represents roughly 16% of the core emission in 3C298 and thereby provides an excellent fit to the 38 K grey-body fit of Podigachoski et al. (2015). We observe strong dust emission towards the nearby western radio lobe, as well as a clump of faint dust emission at the location of the jet deflection, south-east of the core/AGN. The dust is likely linked to the optical disturbance in the 3C298 host galaxy observed by the HST (Hilbert et al., 2016) and to the CO disc reported by Vayner et al. (2017).

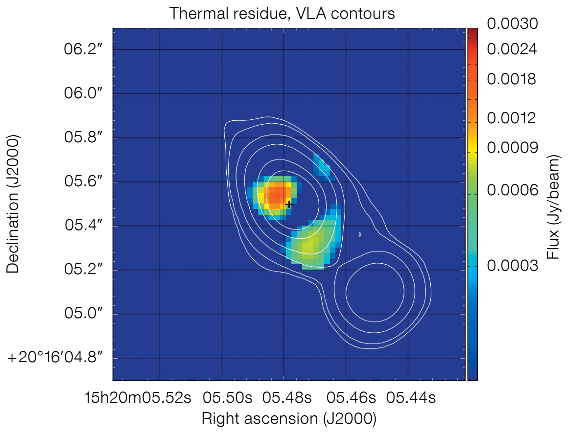
The compact (1.2-arcsecond double) radio source 3C318 was originally thought to be an extremely bright FIR source, but the Herschel imaging of Podigachoski et al. (2016b) showed that a substantial fraction of the FIR flux originates from a foreground pair of interacting galaxies. Nevertheless, the updated FIR data still suggest a SFR of 580 $M_\odot$ year^{-1}, from model-dependent SED fitting. At 0.18-arcsecond resolution, our ALMA 1-millimetre image shows a somewhat resolved core structure of 2.2 mJy integrated strength. As seen from 0.03-arcsecond resolution MERLIN+EVN radio imaging (Spencer et al., 1991), the compact radio double breaks up into a multi-component structure at a position angle of 45 degrees.

We obtained VLA Director’s Discretionary Time (DDT) observations in 2018 to image 3C318 at 2 cm, permitting us to subtract the non-thermal emission from the 1-millimetre image, at the ALMA resolution, after careful alignment of the images. The resulting thermal residue, with radio contours overlaid, is shown in Figure 2; residual thermal emission is seen immediately north-east and south-west of the AGN core, with a total 1-millimetre flux density of 0.23 mJy, which is 11% of the total 1-millimetre flux density. These dust features are perfectly aligned with the elongated, multicomponent, cm-wavelength radio emission, hence their morphology and strength provide strong support for the circumnuclear starburst picture.

Quasar 3C454.0 displays a bent, subarcsecond-sized radio source. We obtained archival VLA 2-centimetre data, yielding an image at a resolution comparable to our ALMA 1-millimetre image, which we subtracted from the latter, after accurate alignment and flux density scaling. The resulting residual thermal 1-millimetre emission, overlaid with the VLA 2-centimetre radio contours, is shown in Figure 3; it is concentrated just east of the optical AGN, elongated roughly north-south, and peaking at the location of the bend in the radio structure. Its integrated strength is 1.9 mJy, which is 18% of the total 1-millimetre flux density. These values do not change the SED-inferred SFR (Podigachoski et al., 2015); they in fact support the circumnuclear starburst picture.

Radio-loud ULIRGs, their ISM, and feedback mechanisms

In summary, all three sample quasars — having compact, subgalactic-sized radio morphologies and strongly suspected to have high SFRs — were found to possess circumnuclear dust structures on



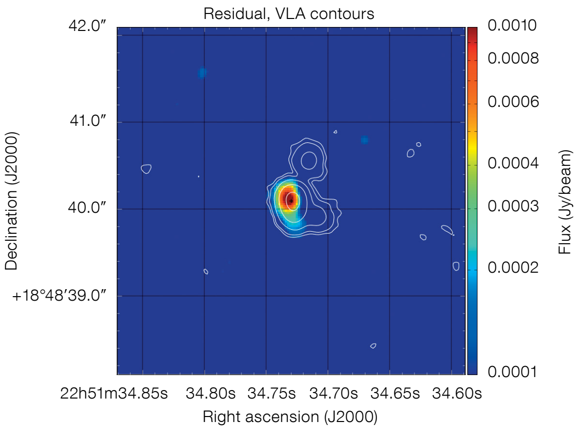


Figure 2. (far left) Thermal dust emission at 1 mm in the host of 3C318, with 2-centimetre radio contours overlaid; the + sign marks the location of the optical QSO.

Figure 3. (left) Thermal dust emission at 1 mm in the host of 3C454.0, with 2-centimetre radio contours overlaid; the + sign marks the location of the optical QSO.

the subarcsecond (kpc) scale. The ALMA resolution of roughly 0.18 arcseconds seems to be crucial to isolating these structures in the 1-millimetre images, which are otherwise dominated by nuclear synchrotron (non-thermal) radiation. The dust morphologies are indicative of radio jet–ISM interaction, and their ULIRG-strength FIR luminosities find a natural explanation in positive AGN feedback, i.e., extra-strength star-formation, driven by the advancing radio jets in the dense central parts of the AGN hosts. In other words, these AGN – which are most likely young – present evidence for positive rather than negative feedback.

What about negative feedback — does the present study shed light on that mechanism? We believe it does, but the negative feedback appears to be starburst- rather than AGN-driven. One of the sample quasars, 3C298, displays outflowing gas winds, seen as so-called associated CIV absorption in the optical QSO spectrum, but also from other ions and molecules, as observed with integral field spectroscopy by Vayner et al. (2017). As we have argued elsewhere (Barthel et al., 2017), there is evidence that such quasar winds have their origin in massive ongoing host starbursts, such as observed locally in Messier 82; 3C298 would be a prime example of such starburst-driven negative feedback. On the other hand, we cannot rule out AGN quenching in more mature and old radio sources (see, for example, Falkendal et al., 2019).

Confirming the intermediate-resolution study of extreme-redshift QSOs by Wang et al. (2013), we find from our high resolution imaging that the symbiotic dusty starbursts are very compact circumnuclear structures, extending a few kiloparsecs from the AGN at most. This is in agreement with the lower-resolution Atacama Compact Array study of FIR-bright SDSS QSOs (Hatziminaoglou et al., 2018). Such compact starbursts have also been observed in luminous submillimetre galaxies (for example, Tacconi et al., 2006; Hodge et al., 2016; Calistro-Rivera & Hodge, 2018), so they may be one and the same phenomenon building up massive galaxies, regardless of whether there is active massive black hole (MBH) accretion or not.

Finally, our identification of the cool dust emission as originating from a starburst gives confidence that the mechanism is the hitherto tacitly assumed source of the long-wavelength far-infrared emission (that is to say in the SED modelling — for example, Barthel et al., 2012; Leipski et al., 2014; Ma & Yan, 2015; Podigachoski et al., 2015; Pitchford et al., 2016; Westhues et al., 2016). Given the frequent incidence of ultraluminous ~ 40-K dust emission in high-redshift AGN, the symbiotic occurrence of starbursts and black hole buildup must be widespread.

To be continued

These intriguing observations call for several follow-up studies. Firstly, higher-resolution ALMA 1-mm imaging is now possible, permitting the examination of the morphological details of the jet-star formation interaction. Secondly, ALMA spectroscopy can determine the kinematics of the gas involved in the feedback mechanism, including the postulated starburst-driven superwinds. Thirdly, control samples of low-SFR 3C AGN, in compact, young as well as large, mature radio sources, must be studied with ALMA and compared with the high-SFR objects. Concerning the more distant future, JWST imaging may reveal the newly formed circumnuclear star clusters.

Acknowledgements

We acknowledge our long-time collaborators Pece Podigachoski, Martin Haas and Belinda Wilkes for exciting years of study of an exciting AGN sample. Thanks are also due to our ALMA project co-I's Carlos De Breuck and George Djorgovski, to the VLA Director for granting us DDT time in 2018, and to Jack Radcliffe for data processing advice. Finally, the assistance of the Netherlands ALMA Regional Center is gratefully acknowledged.

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N. Lira - ALMA (ESO/NAOJ/NRAO)

Above: On 17 April 2019, the Senate of Chile awarded ALMA a medal for its instrumental role in capturing the first-ever image of the shadow of a black hole. The image produced by the Event Horizon Telescope image used eight radio facilities. ALMA and APEX, in which ESO is a major partner, played a key role in this result.

Below: ESO signed contracts for the manufacture of the ELT M5 mirror with the French companies Safran Reosc and Mersen Boostec.

ESO/M. Zamani

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The New ESO Phase 1 System for Proposal Submission

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On 1 April 2019 ESO released its new Phase1 system (p1) for the submission of Director's Discretionary Time (DDT) observing proposals for the period between April and September 2019 (Period 103). The p1 interface will be extended to all types of observing proposals in the Period 105 Call for Proposals, which will be released in September 2019. This represents the first part of a broader overhaul of the ESO Phase 1 system that also entails a significant modernisation of the Observing Programmes Committee peer review process and associated tools. Here we highlight the main features of the new user interface for proposals submission.

The new p1 system: an overall view

The upgrade of the current ESO Phase 1 system is a major undertaking, consisting of three main interfaces: the User Interface (UI) for the submission of observing proposals; the interface for the evaluation of the proposals; and the interface for the management of the entire Phase 1 process, from the preparation of the Call for Proposals to the release of the telescope schedule and user notifications at key stages of the process.

Phase 1 is fully embedded in the ESO Data Flow System, an integrated collection of software and hardware that facilitates the flow of scientific and operational information for the VLT (see Hainaut et al., 2018; ESO, 1998). Changes to Phase 1 can therefore impact many other tools and operational phases. This provides an opportunity for better integration with the various operational workflows, ensuring a smooth transfer of all the key information from one phase to the next. Because of its very broad scope, the project has been divided into two parts: the user interface for proposals submission, and the management of the review process. The review of the proposals is carried out by the Observing Programmes Committee (OPC). The interface for the proposal submission part was released very recently, at the start of Period 103, for the submission of DDT proposals; the peer review management part of the project is currently being developed.

Probably the most relevant change at the heart of this upgrade is the move from the old ESOFORM package and stand-alone tools to web-based technology. The system is implemented using Google's Angular[1] and Semantic UI[2] frameworks for the client side, whereas the server side is based on the Java Grails framework[3]. It is expected to work on up-to-date versions of web browsers on any operating system. The new p1 proposal submission user interface uses the same look and interface conventions as the recent p2 tool, which is also shared by other tools being developed (exposure time calculators, and the Observation Preparation tool) to ensure a seamless user experience independently of the operational phase. Beyond the look and feel of the interface, this sharing of technologies also ensures that p1 will be integrated with other tools that implement the Data Flow System, i.e., p2, followed by the exposure time calculators and preparation software.

The p1 interface now uses the same abstraction to describe the actual physical instruments on the telescope as the other systems (Instrument Packages, used for instance for p2 and at the telescope), ensuring that p1 is always aligned and synchronised to the latest status of each instrument.

The system includes many new features, including allowing the Principal Investigator (PI) and Co-Investigators (Co-Is) to edit proposals in a collaborative way, graphically plotting target visibilities and the probability of realising the requested observing conditions. One can also retrieve target information directly from the Centre de Données astronomiques de Strasbourg (CDS) Sesame[4] or upload them from a CSV file. Finally, a submitted proposal can now be updated right up to the deadline — previously changes to a submitted proposal could only be made by submitting a newer version and withdrawing earlier submissions.

There are also some practical implications, the most notable being the impossibility of directly submitting existing LaTeX proposals into the new system — a straightforward manual conversion is required. Furthermore, each of the Co-Is is now required to have an ESO User Portal account[5]; the PI will add them to the proposal using their email address.

How to submit observing proposals via the new p1 User Interface

Being web-based, the new p1 system does not require any specific tool or package to be downloaded beforehand. Once logged into the User Portal, you just follow the link *Submit an observing proposal* in the Phase 1 section. Although some important features have changed — for example, the definition of an observing setup is done via a menu and time constraints are expressed in a different way — all the key components of the old classic LaTeX observing proposal are still there.

The left part of the interface is a list of all your proposals. Figure 1 shows the workflow menu, which is displayed for each proposal. In the following, we will guide you through the various steps, highlighting those that have changed the most.

As soon as you create a *New Proposal*, a dynamical checklist appears in the main window, summarising the actions that you need to take before you can submit the proposal. The checklist is understandably long at the very start, but it quickly reduces as you start to work through the various steps. In this way, last-minute surprises, such as having a proposal rejected because of some obscure error, are removed; once the checklist is empty, you can submit the proposal.

The first item on the left-hand menu (Figure 1) is the *Summary*, which is intended to provide an overall view of the proposal,

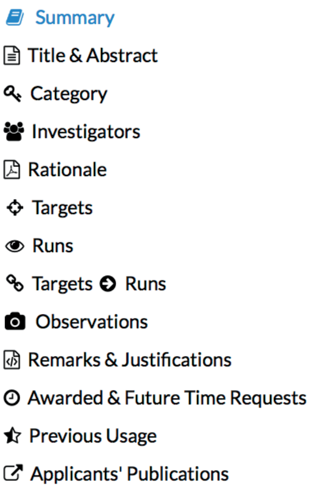


Figure 1. The left-hand menu of the new p1 user interface outlines the various steps to be followed in the preparation of an observing proposal. The order in which the steps are listed does not necessarily reflect the order in which these steps should be completed.

starting with the Programme ID, which will be assigned only after you submit the proposal. The format of the Programme ID has also changed; taking as an example, *104.20C8*: here 104 is the cycle in which the proposal is submitted, and 20C8 is a unique identifier. Then come the Programme Type, *Cycle*, and current *Status* of the application. The proposal will change its status from Draft (while working on it), to Submitted once the proposal has been submitted (via the *Submit* button) and the status will become "Valid" as soon as the call has closed (i.e., as soon as the proposal submission deadline has passed). DDT proposals are an exception, as their status goes directly from "Draft" to "Valid". A proposal that has been retracted by reopening an already submitted proposal (by clicking on *Unsubmit*) will not be validated unless it is resubmitted. Each of the proposal sections can be edited directly from the *Summary* window or via the left-hand menu.

When adding *Investigators* (every team member must be registered in the ESO User Portal), the PI can search for them by typing their (exact) e-mail address in the search field. The PI is asked to assign a role to each of the Co-Is, the options being Co-I or delegated PI (dPI). Although the ultimate responsibility for the content of the proposal will always lie with the PI, a dPI has the same privileges as the PI (for example, submitting/retracting the proposal, or changing the list of collaborators). Beware that as PI or dPI you can strip yourself of your respective privileges while assigning these roles, hence blocking any further management rights for that proposal.

The *Scientific Rationale* has kept its original structure, but now must be uploaded as a PDF file. Templates are available in the following formats: Google Docs, Microsoft Word and LaTeX. While there is no systematic check on the uploaded PDF file, proposals whose scientific rationale template has been tampered with (for example, by reducing the font or narrowing the margins) will be ignored. That said, you have the freedom to adjust the layout, for instance to include figures.

Targets can be uploaded from a CSV file — if several targets are required, the minimum set of parameters is "Name, Right ascension, Declination, Magnitude". Each of these can also be added to the proposal by typing its identifier in a dedicated pop-up window that resolves it automatically (via Sesame). Targets will then have to be associated with runs once these have been created. Note that for instruments or modes requiring a reference star, that star has to be defined as a target together with the science objects.

The basic concept of *Run* has not changed with respect to the old Phase 1, i.e., a run remains the minimum schedulable coherent entity, defining a series of observations to be performed with one instrument, with a common set of observing constraints (that is, all the observations require conditions that have the same probability of realisation), and sharing the same run type and observing mode.

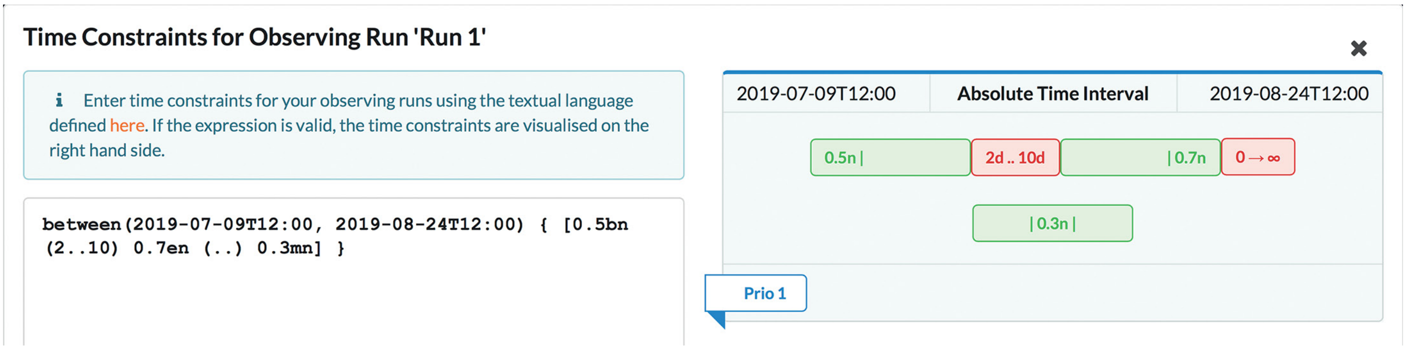
Once the high-level characteristics of a run have been defined, the instrument setups come next. The choice of what is available is now offered via pull-down menus, that guide the user to the successful definition of feasible combinations of setup elements. Those users already familiar with the ESO p2 system will recognise many features but will find fewer items because only those elements relevant to Phase 1 (i.e., necessary for scheduling the observations and for performing the technical feasibility reviews) are available.

Another major improvement offered by the new p1 user interface concerns the definition of time constraints. These are specified at run level (look for the little clock icon) and with a customised syntax[6]. The interface allows for both absolute and relative time constraints and offers an immediate visualisation of the constraint (see Figure 2 for an example).

Using the *Targets → Runs* section, you can assign science targets to each of your runs. This will automatically define a series of observations, one for each observing setup defined in that run for each assigned target.

The last remaining major step of any observing proposal is the final computation of the telescope time needed to carry out the proposed observations (via *Observations* in the left-hand menu). The p1 user interface offers three views of telescope time: at the level of individual observations; at the target level (should a target be observed in multiple observations); and at the run level. Following a bottom-up approach, one must first define the time needed for each observation; here, one can simply fill in the blue box labelled *Telescope Time* (with one observation; i.e., integration time + all overheads[a, 7]) or alternatively, specify the details of the individual components of each observation. We recommend the latter approach, at least for a small number of observations, so that the time request can be better evaluated during technical feasibility. Multiple exposures of the same observations (for example, to reach a deeper magnitude, to perform a mapping mosaic, or to monitor the variability of the target) or the wish to skip a given observation can be specified by using the *Repeat* field. These bottom-level exposure times *Telescope Time* (with one observation) are then propagated to compute the telescope time (*Tel. Time* in the blue boxes) at the target and run level.

The *Remarks & Justifications* section gathers all possible explanatory/commentary fields in one place. All fields are



Time Constraints for Observing Run 'Run 1'

Enter time constraints for your observing runs using the textual language defined here. If the expression is valid, the time constraints are visualised on the right hand side.

```
between(2019-07-09T12:00, 2019-08-24T12:00) { [0.5bn
(2..10) 0.7en (..) 0.3mn] }
```

Figure 2. A graphical representation of a special case of time constraints. These are defined in the p1 interface using a dedicated, intuitive and well documented syntax (left) and immediately displayed in graphical form (right) to enable “sanity checks”. In this specific example, the user is requesting a total of 1.5 nights distributed as one 0.5-night allocation, followed by 0.7 nights (at least 2 days after, and within 10 days of, the first 0.5 nights), completed with a final allocation of 0.3 nights, any time after the preceding allocation. Note that one can now specify even the part of the night (beginning, middle or end) when the observations should preferably be scheduled.

mandatory, but one can always specify N/A (Not Applicable) for some of them. The most important ones remain the justification of the specified constraints and the telescope time requested. This section also includes the more technical/operation-related comments related to the specified telescope, observing mode and requested calibration. Target duplications with Guaranteed Time Observation (GTO) programmes and/or ESO Science Archive must be declared and clarified in the corresponding text boxes.

Finally, *Previous Usage* and *Applicants’ Publications* complete the information that needs to be provided in terms of previous time allocation (to keep track of what is happening with previous sets of data) and publications with relevance to the subject of the proposal from the proposing team.

The p1demo testing environment

A dedicated p1demo[8] environment has been set up so that users can experiment with the new p1 system before the official release of the next Period 105 Call for Proposals (foreseen for the end of August 2019). Please remember this is a public space; due care should be taken not to share confidential or sensitive information. Any user can use this environment to create a full proposal and test its submission and retraction. It includes the possibility of experimenting with preparing proposals using the entire suite of instruments of the La Silla Paranal Observatory, selecting all observing programme types — i.e., Normal, Large, GTO, GTO-Large, Monitoring and Calibration — and all observing run types: Normal, Target of Opportunity (ToO)-Soft, ToO-Hard, ToO-RRM (Rapid Response Mode).

Each step in the proposal preparation workflow is introduced by a short, informative (blue) box, supplemented by a more extended description of that specific step (mini-help). Many parts of the new proposal submission system resemble the old ESOFORM structure (Title, Abstract, Category, Investigators, and all ancillary information). More extensive help is available from the menu of the user interface, and via a help button at the top of each page. The p1demo environment also has some realistic proposals, and a commented proposal in which each field contains additional information and tips.

As already mentioned in previous sections, the biggest changes relate to how runs and observations are defined. Therefore, we recommend that users who plan to submit observing proposals at the next deadline familiarise themselves with the new interface beforehand. A short video-tutorial is also available[9].

The next steps

Although the feedback received so far has been positive, the full release of the new p1 user interface for the Period 105 Call for Proposals represents our next major milestone. Once this is accomplished, our focus will move to the OPC management part, i.e., all proposal traffic between the Call for Proposals deadline and the conclusion of the OPC process. Our aim is to offer the OPC referees a user-friendly interface whereby they will be able to follow all steps for the evaluation of proposals in one view — declarations of conflicts of interest, updates in review assignments, grading, review comments, etc. This will mean that the department overseeing the review process — the Observing Programmes Office (OPO) — will also benefit from this view in carrying out its daily business in support of the OPC. This represents a major step forward compared to the several different tools and views currently in use, not to mention all the manual interventions that take place.

At the same time, the User Portal will also be upgraded to support the introduction of scientific and technical keywords that most closely define the expertise of each professional astronomer registered in the portal. We will then be able to experiment with more detailed proposal assignment algorithms that are based, for instance, on expertise keyword matching. Another foreseen change that will impact the proposal preparation is how affiliations will be defined. ESO has decided to follow the official Global Research Identifier Database (GRID)[10] list, which is based on a very high-level differentiation of institutions (no more departments, groups, addresses, etc). Finally, in order to monitor — and mitigate — possible biases in the review process, the portal will request that all users specify their gender.

Any queries, comments and feedback on the new p1 system are very welcome via a dedicated e-mail address[11]. We are always keen to receive constructive feedback.

Acknowledgements

The authors would like to thank all the ESO staff members and contractors who got involved in the project and made important contributions at different development phases. In particular, special thanks go to all the scientists in the User Support Department and Paranal Science Operations, and in particular Andrea Mehner. Moreover, all beta testers are thanked for their engagement and feedback, especially the members of the ESO Users Committee. Finally, special and warm thanks go to all colleagues in the Observing Programme Office (who had to bear with us on the bumpy road leading to this release) and Gaitee Hussain, former OPO staff member, for her involvement in the early phases of the project and for her precious proofreading of p1-related material.

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[1] Google Angular framework: https://angular.io
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[3] The GRAILS project: https://grails.org
[4] CDS Sesame: http://cds.u-strasbg.fr/cgi-bin/Sesame
[5] The ESO User Portal: http://www.eso.org/UserPortal
[6] The format of the time constraints is described here: https://www.eso.org/p1demo/timeConstraintsHelp
[7] Overheads table: https://www.eso.org/sci/facilities/paranal/cfp/overheads.html
[8] The p1demo interface: https://www.eso.org/p1demo/proposals
[9] A p1 video tutorial: https://www.eso.org/sci/observing/phase1/newP1tool/p1_shortIntroVideo_new.mp4
[10] Global Research Identifier Database (GRID): https://www.grid.ac
[11] E-mails can be sent to the p1 team at p1@eso.org
[12] The p2 demo interface: https://www.eso.org/p2demo/login

Notes

[a] The overheads are the same as in p2; if you are already familiar with the overheads that apply to your particular instrument setup, you can use the overheads table[7], otherwise it is recommended that you experiment with the p2demo[12].

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Report on the ESO Event

20th Anniversary of Science Exploration with FORS

held at the ESO Supernova, Garching, Germany, 12 March 2019

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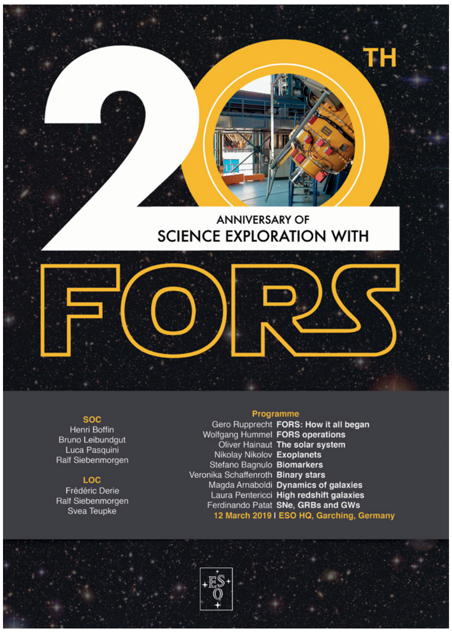
Henri Boffin[1]
Frédéric Derie[1]

[1] ESO

About 50 scientists belonging to the “Friends of FORS” family convened at the ESO Supernova Planetarium & Visitor Centre to celebrate 20 years of successful science exploration with FORS1 and FORS2. Scientific highlights from these instruments were discussed, covering various research areas ranging from interstellar bodies entering our Solar System, to the detection of exoplanets and biomarkers, interstellar medium dust polarisation, binary star velocities, galaxy dynamics, high-redshift galaxies near the re-ionisation epoch, and transient astronomical events such as supernovae, gamma-ray bursts, and gravitational waves. In addition to reviewing the amazing scientific achievements from the FORS instruments, a specific goal of the conference was to discuss ways in which to foster the high scientific impact of the instrument in the future. Various suggestions from the ESO community for upgrading the instrument were presented and discussed.

A successful twin

The FOcal Reducer and low-dispersion Spectrpgraphs, FORS, are two multi-mode instruments mounted on a VLT Unit Telescope (UT) Cassegrain focus. They are offered in several modes: imaging, polarimetry, long slit, and multi-object spectroscopy. In April 1999, the first of the twin workhorses of the VLT, FORS1, began science operations. In September 1999 FORS2 arrived at Paranal, entering into regular service in April 2000. Over the years, the two FORS instruments have provided unique data leading to many astronomical discoveries. Both instruments are among the most prolific instruments worldwide. In March we celebrated the scientific discoveries made with these successful instruments in



Credit: N. Boffin

Figure 1. The conference poster.

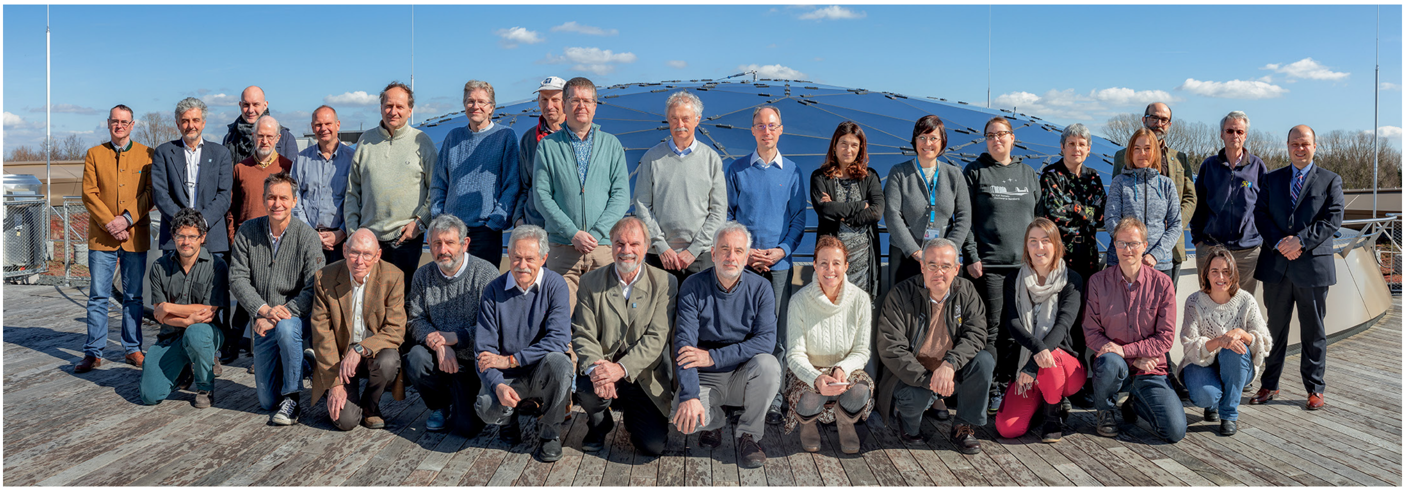


Figure 2. The conference workshop photograph.

a one-day event. The goal of the conference was to gather, consolidate and understand the wishes and needs of the astronomical community for upgrades that would ensure the high science productivity of FORS into the future.

Instrument features

FORS is the "swiss army knife of the Paranal Observatory". FORS observations cover a wide wavelength range from 330 to 1100 nm at high sensitivity; the transmission is above 60% over 360–1100 nm, and reaches almost 80% around 440 nm. In imaging mode this leads to a typical magnitude limit of about 25.9 in *U* (with 1-hour integration; S/N ~ 5), 27.6 in *B* and 27.3 in *V* using an E2V detector, and — with the MIT detector — 26.6 in *R*, 25.8 in *I*, and 24.7 in *z*. The field of view is 6.8 × 6.8 arcminutes, which is the maximum unvignetted field of the Cassegran focus at the VLT. High image quality is ensured by a passive flexure compensation system.

The system includes a longitudinal atmospheric dispersion corrector (LADC) which acts up to about 60 degrees away from zenith, i.e., airmass $\lesssim$ 1.5–1.6. The astrometric precision reached is about 0.1 milliarcseconds using the high-resolution collimator. The instrument can also be used in spectroscopic mode with a magnitude limit between 23 and 24 in *V* as well as in imaging and spectroscopy polarimetry. FORS2 spectroscopy consists of three modes: classical long-slit spectroscopy with slits of 6.8-arcminute length and predefined widths between 0.3 and 2.5 arcseconds; multi-object spectroscopy using 19 slitlets with slit lengths of 20–22 arcseconds each; and arbitrary widths created by movable slit blades. Multi-object spectroscopy may also use masks with slitlets of almost arbitrary lengths, widths, shapes and angles in the Mask eXchange Unit mode (MXU). There are 15 grisms with resolutions from 260 to 2600 for a 1-arcsecond slit, which may be combined with three different order-separating filters to avoid second-order contamination.

Science impact

Both FORS instruments have been in high demand since first light, and this has not changed; FORS2 is still among the most requested instruments at the VLT, with more than 100 proposals submitted in Period 102 (12% of all VLT proposals). In terms of refereed papers, the FORS instruments are the most productive instruments at Paranal; FORS1 led to 1022 refereed publications, and for FORS2 this number is 1511. In 2017 alone, FORS2 led to 106 refereed publications. Among these were three Nature papers highlighting innovative results: the first interstellar asteroid detected in the solar system (Meech et al., 2017; Micheli et al., 2018); the spectroscopic identification of a gravitational wave source (Pian et al., 2017); and the first detection of titanium oxide in the atmosphere of an exoplanet (Sedaghati et al. 2017; Nikolov et al. 2018). Over the years, FORS2 has led to 29 Nature papers and 10 Science papers. Apart from those mentioned above, these papers cover a variety of topics, including asteroids, binary stars, neutron stars, supernovae, black holes, gamma-ray bursts, and quasars. All modes of FORS2 were used for these discoveries.

A presentation of early science with FORS can be found in Rupprecht et al. (2010). At that time, they stated that *"if we look at the number of citations of VLT papers, it is symptomatic that at least one of the two FORS instruments was involved in eight of the ten most cited VLT papers"*. Amongst the most cited FORS2 papers, one finds the spectroscopic studies of the GOODS-South field (Vanzella et al., 2008; Popesso et al., 2009; Balestra et al., 2010) and of the Chandra Deep Field-South (Szokoly et al., 2004), which are based on MXU observations. In more recent years, the most cited papers are about Lyman-α emitters in the early universe (with MXU), spectropolarimetry of massive stars and dust, photometric studies of young stellar regions, astrometric studies of brown dwarfs and transmission spectroscopy of exoplanets.

The workshop

In his welcome talk, the Director General presented some of his own science that had been carried out with FORS, identifying X-ray sources from XMM-Newton serendipitous surveys (Barcons et al., 2002).

He stressed the high scientific impact that FORS has delivered over the past 20 years. The first of several FORS project scientists from the past 20 years was Gero Rupprecht and, in a very emotional talk, he reflected on the early days of the instrument — during commissioning. He explained how FORS1 received the nickname of “yellow submarine” in the early days owing to its distinctive colour. Former Consortium member Wolfgang Hummel — now at ESO — highlighted the sophisticated operational model that had been put in place to make sure the best science is done with the instruments. He also presented a brief history of the various changes to the instruments.

The scientific presentations started with a review by Olivier Hainaut of the characterisation of minor bodies in our Solar System. Particular attention was given to ‘Oumuamua, the first and currently only asteroid ever detected which is of interstellar origin.

Nikolay Nikolov presented the transmission spectroscopy technique, which is used to characterise the atmospheres of exoplanets, from hot gas giants down to cooler Earth-mass worlds. He stressed that the resulting FORS2 light curves were of space-based quality, making FORS2 the best ground-based instrument in the world for this kind of science. This is important as the VLT has access to fainter targets that have smaller signals than the Hubble Space Telescope does. Also, in the future all space-based instruments will only access the infrared and FORS2 will be needed to provide the optical counterpart observations, ensuring a unique role for FORS2 over the next 10–15 years.

Stefano Bagnulo showed how FORS2 spectro- and imaging polarimetry have been used in the study of supernovae, to characterise interstellar dust, and to explore the surfaces of Solar System bodies. Of special interest is the study of how polarised radiation reveals biomarkers, such as O_2, in a planetary atmosphere that is known to host life — i.e., the Earth (Sterzik et al., 2012)!

The challenges associated with observing short-period binaries were discussed by Veronika Schaffenroth. The FORS resolution is sufficient to measure radial velocity curves, and hence masses of close binaries — assuming the orbital inclination is known. One notable case involved using FORS observations to constrain the minimum mass a companion must have to be able to eject the envelope of the primary star in a common envelope (CE) phase. Such a phase, which is very poorly understood, is critical in creating very short period binary systems, some of which are thought to explode as Type Ia supernovae and to produce gravitational waves.

The dynamics of galaxies and clusters as revealed by FORS was presented by Magda Arnaboldi. The motions of planetary nebulae allow the mass distribution in the outer halos of galaxies, and in the cores of galaxy clusters, to be determined (McNeil et al., 2010; Spiniello et al., 2018). This requires the use of a special technique, called counter-dispersion imaging, which involves doing slitless spectroscopy, combined with narrowband filters and superposing two images taken 180 degrees apart. Thanks to this, it is possible to measure distances and radial velocities out to 25 Mpc.

An outstanding issue in modern astrophysics is what reionised the Universe and when and how the first objects formed. Laura Pentericci showed what was the main initial goal of FORS when conceived, i.e., deep spectroscopy to identify a large population of Lyman-α emitting galaxies up to $z > 7$ (Vanzella et al., 2008). She presented the deepest FORS2 spectrum ever obtained in the reionisation epoch — a 52-hour-long exposure that showed… nothing! This in fact indicates that reionisation might be a more extended process than previously thought and not yet completed at $z = 6$.

Figure 3. The FORS team during the preliminary design review in 1992.

Finally, Ferdinando Patat presented FORS as a versatile tool for transient astronomy and presented highlights of results obtained with the instruments in the field of supernovae, gamma-ray bursts and, more recently, on the electromagnetic counterparts of gravitational-wave events. The abstracts and presentations of the talks are available at the conference website[1] and a booklet[2] has been prepared that collects the highlights of 20 years of science exploration with FORS.

The future

The conference summary focused on a discussion of the various upgrade options as presented. The need for a larger field of view was frequently raised; however, the unvignetted field of the VLT Casegrain focus is already in use. In terms of the telescope itself, an enhanced cleaning procedure to ensure optimal sensitivity of the ADC was requested. The instrument was designed for a 10-year lifetime (!), so a general overhaul of the mechanics and electronics is needed to ensure its smooth operation for the next 15 years. At the same time, the instrument will be upgraded so that it provides higher transmission in both the blue and red parts of the optical spectral range, without the need — as is currently the case — to exchange CCDs. The detector will come with better cosmetics and reduced systematics in the flat field. New grisms that provide flatter throughput and higher sensitivity will also be procured. The need for specific high-spectral-resolution grisms centered on the Na, K, and Li lines was also identified.

FORS polarimetry was reported to be excellent, though it could be further improved by reducing systematic errors such as the instrumental polarisation. A higher precision in Stokes V/I could be attained by considering a double-wedge device, allowing simultaneous observations of all four components of the Stokes vector rather than recording just the ordinary and extraordinary beams. In that respect, all the optical devices, including the collimator, will be verified and birefringence reduced where possible. An interest in imaging polarimetry with flat instrumental polarisation across the field was discussed. Besides bringing all software systems up to the current standards, the importance of the pipeline was stressed, including the need for science grade data products. Finally, it was also imperative to review all the operational constraints, such as for example the interdiction on taking arcs during the night at the position of the observations.

Demographics

The Science Organising Committee sought fair representation from the community when voting to invite eight speakers. The end result was a male:female ratio of 4:3 among the invited science speakers.

Acknowledgements

We appreciate and thank the FORS Consortium members, and Immo Appenzeller in particular, for attending this special event. We would also like to thank Svea Teupke for the very efficient logistics support.

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Links

[1] Workshop programme, abstracts, and online presentations are available at: https://www.eso.org/sci/meetings/2019/FORS2019.html

[2] FORS science overview booklet available at: https://www.eso.org/sci/meetings/2019/FORS2019/FORS20thyear_low.pdf

Image from first light FORS *BVRI* observations of the spiral galaxy NGC 1288 on the night of 15 September 1998.

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Report on the ESO Workshop

Linking Galaxies from the Epoch of Initial Star Formation to Today

held at Rydges World Square Center, Sydney, Australia, 18–22 February 2019

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We report on the first joint Australia–ESO conference since the start of the Strategic Partnership. The conference was supported by ESO, the Australian Academy of Science (under a research grant from Elizabeth & Frederick White), the Australian Government Department of Industry, Innovation and Science, the Independent Research Fund Denmark, Macquarie University, the International Centre for Radio Astronomy Research, CSIRO Astronomy and Space Science (CASS), and Astronomy Australia Limited. The scientific organising committee (SOC) took several measures to tackle unconscious bias while preparing an exciting programme with good gender balance and greater representation from early career researchers. We detail our approach here with the aim of helping organisers of future conferences.

Over the last two decades, surveys mapping the Universe have made clear that star formation activity peaks at redshift $z \sim 2.5$ (known as "cosmic noon"). The driver of this cosmic behaviour is still an open area of research. A better understanding of star-forming regions and physical processes is required to explain the rise and fall around the cosmic noon. With existing observational resources, we are able to resolve many detailed questions about the physical processes driving galaxy formation and evolution, including:

- The enrichment of the interstellar medium with metals and dust and the subsequent effects on star formation.
- Gas infall from, and outflow to, the intergalactic medium.
- The role of galaxy environment and mergers.
- Triggering mechanisms of starbursts, and active galactic nuclei and their feedback to the surrounding medium.
- The role and impact of gas dynamics and stellar kinematics.

Cosmological simulations (Illustris[1], EAGLE[2], FIRE[3]) indicate that the interstellar medium and its constituents are important to understanding galaxy formation but are vastly unconstrained observationally. The discrepancy between observations and simulations is because the roles and physics of the above-mentioned processes are not well constrained.

The five-day conference attracted a wide cross-section of the international astronomical community and included representatives from 19 countries making up a total of 162 attendees (see Figure 1) with the aim of better understanding star-forming regions and the various physical processes in galaxies. Of particular interest was the availability of 3D data allowing the stellar and gas kinematics to be spatially resolved, as well as other physical tracers (for example, metallicity). This has become possible thanks to large surveys with integral field unit (IFU) spectrographs, for example, the survey with the Sydney-AAO Multi-object Integral field spectrograph (SAMI), Physics at High Angular resolution in Nearby GalaxieS (PHANGS), survey with the Multi Unit Spectroscopic Explorer (MUSE) on the VLT and TYPHOON (D'Agostino et al., 2018). There is a very strong synergy between these surveys — many of which are conducted in Australia — and current and future ESO facilities. One important aspect is the complementarity between the programmes and science data products in the ESO science archive facility and the AAO data centres; many of these have become available thanks to the ESO public surveys and the reprocessing of surveys carried out with Australian facilities. The collaboration between these two data centres allows for the cross matching of resources for a multi-wavelength exploration of the objects in our Universe.

The conference offered an opportunity to summarise the current status of the field of galaxy formation and evolution and to discuss how to maximise the scientific return in the future. In addition, several updates on small and large ongoing surveys were provided. After a comprehensive range of talks the main scientific outcome of the conference was that spatially resolved observations and simulations of the galaxies are being extended to the circumgalactic medium of galaxies. In addition, the spatial resolution and sensitivity of the current generation of instruments is powerful enough to trace multiple physical parameters of galaxies (for example, gas and stellar dynamics, metallicity, and age) out to the edges of the galaxies.

The workshop webpage[4] has many more details, including more information

Figure 1. Conference photo.

about the programme, participants and organising committees. The talks have been collected and are available using Zenodo[5].

Demographics

As this was the first ESO-supported conference held in Australia, it was important to attract both the ESO and Australian communities. The timing was carefully chosen to be at the end of the Australian summer break, coinciding with winter vacations in several European countries. The support provided by our eight sponsors allowed us to keep the registration fee relatively low. As shown in Figure 2, these factors helped to achieve our goal, with more than half of the participants coming from overseas — not easy, given the time and costs associated with travel between Europe and Sydney.

During the organisation of the conference, we paid particular attention to including as many participants from the community as possible by controlling various biases in the selection of participants (for example, gender, seniority, and geographic distribution). The SOC decided to anonymise the contributed abstracts prior to ranking them in order to avoid unconscious bias. Furthermore, the SOC members were asked to declare any conflicts of interest with abstracts and excluded from reviewing them. In addition, votes from the SOC themselves were anonymised — i.e., the votes cast for a particular abstract were not associated with the corresponding SOC members. All of these measures served to reduce hidden biases.

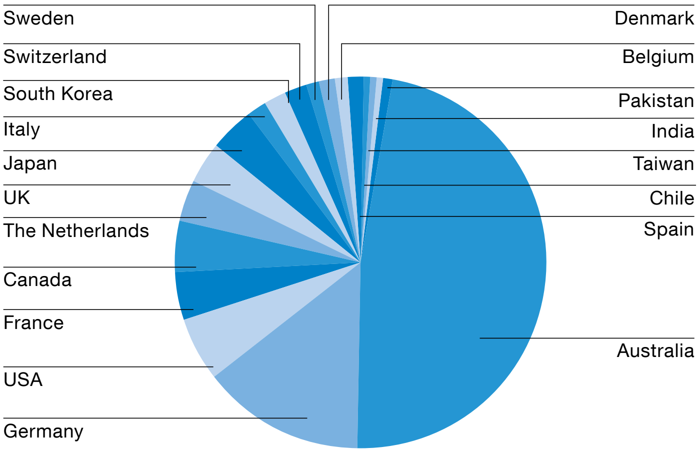

Figure 2. Chart showing the fraction of attendees from various countries; there were 162 attendees in total.

The conference had 26 invited and 73 contributed talks and 23 poster presentations ("sparklers"). Thanks to the anonymous voting, the conference achieved a very good gender balance, and there were several science presentations from students and early-career researchers (see Figure 3). This gives one of the best examples of an astronomy conference which set out to improve representation, particularly amongst female and young/early career researchers. We note that this selection did not compromise on the science; on the contrary, many participants found it enlightening and refreshing to see so many new faces and topics amongst the speakers.

Acknowledgements

We would like to acknowledge financial support for this meeting from the Australian Academy of Science (AAS), the Independent Research Fund Denmark, the Department of Industry Innovation and Science Australia, ESO, the Research Centre for Astronomy, Astrophysics & Astrophotonics, Macquarie University (MQAAAStro), the International Centre for Radio Astronomy Research (ICRAR), CSIRO Astronomy and Space Science (CASS), and Astronomy Australia Limited (AAL).

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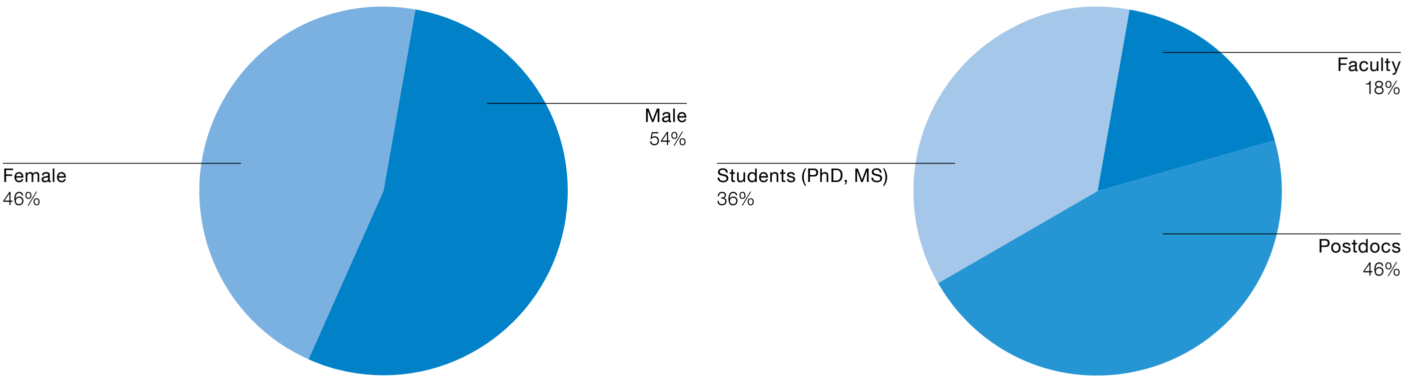
Links

[1] Illustris simulation: http://www.illustris-project.org
[2] Evolution and Assembly of GaLaxies and their Environments (EAGLE): http://icc.dur.ac.uk/Eagle
[3] Feedback In Realistic Environments (FIRE): https://fire.northwestern.edu/about-fire
[4] The workshop homepage: https://www.aao.gov.au/conference/australia-eso-conference-2019
[5] The collection of presentations (via Zenodo): https://zenodo.org/communities/esoaus2019

Figure 3. Left panel: The gender ratio amongst participants. Right panel: The distribution according to career level for all invited and contributed talks, and poster presentations.



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ESO Science Ambassadors

Chris Harrison[1]
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The Science Ambassador project, initiated by ESO Fellows from Garching and Vitacura, is designed to disseminate information about ESO's activities by sending scientists to visit countries across Europe and Chile. The primary goals are: (1) to raise awareness of ESO's mission and its telescopes, with a focus on the Extremely Large Telescope; (2) to transmit the ESO Supernova Planetarium & Visitor Centre experience to schools and the general public; and (3) to promote opportunities at ESO for early-career researchers. The project also provides a long-term legacy through training of local educators and donation of resources.

Motivation and objectives

The last two years have seen a lot of exciting progress at ESO. The construction of the main structure for the Extremely Large Telescope (ELT) — the largest optical telescope ever conceived — is now under way in Chile. ESO facilities have played key roles in recent revolutionary scientific discoveries, including the first ever detection of an electromagnetic counterpart to a gravitational wave event (Smartt et al., 2017) and the first test of General Relativity around a supermassive black hole (GRAVITY Collaboration et al., 2018). Furthermore, 2018 also saw the opening of the ESO Supernova Planetarium & Visitor Centre[1], a facility that showcases much of the fantastic educational and publicity work done by ESO and its partners, including the creation of inspiring exhibition material, planetarium shows and educational workshops.

These recent developments at ESO inspired the fellows to collectively apply for funds that could be used to send ESO scientists to visit public observatories, science festivals, universities and teachers' conferences to promote these achievements. The project was awarded a grant by the Director for Science to carry out engagement activities in 2018. With some careful budgeting and additional fundraising by the fellows, the project has been carried on into 2019.

The most important concept of the Science Ambassador project is that the Ambassadors should directly engage with audiences who have no familiarity with ESO. While the ESO Supernova is an important way in which ESO can interact with the public, visitors tend to come from Germany or privileged European schools that are able to organise travel to Garching. Indeed, several fellows observed that many people they spoke to in their own home countries had little knowledge of ESO, its telescopes or its scientific achievements. Consequently, the main objective of the Science Ambassador project is to promote ESO's mission in astronomy from several perspectives to a broader audience.

The three key goals are:

1. To raise awareness of ESO's mission of running cutting-edge astronomical facilities (with a focus on the ELT) amongst diverse audiences, including university students, teachers, minority groups and the wider public.
2. To promote and donate educational resources created for the ESO Supernova to teachers and public observatories.
3. To attract exceptional scientific talent by promoting opportunities for early-career researchers at ESO in Garching and Vitacura.

The Ambassadors

The activities have been primarily carried out by a team of Science Ambassadors made up of ESO Fellows and students based in Garching or Vitacura. ESO Fellows and students are a very diverse international group, able to communicate key messages and activities in many different languages. In most cases the Science Ambassadors visit their home countries to carry out face-to-face engagement activities. They use their links to people in their own countries to find relevant events or groups to engage with and this has the advantage of easing the organisational aspects of the project. Crucially, people find these early-career scientists from their own countries to be fantastic role models, thus effectively making these ESO Fellows and students great international ambassadors for ESO.

The Ambassadors themselves gain many benefits from leading these activities. Engaging with fun audiences that tend to be much less sceptical or critical — at least compared to researchers! — keeps the Ambassadors enthusiastic and inspired about their own research and they are able to hone their communication and teaching skills. In many cases the Ambassadors have the opportunity to promote their own specific research topics during their trips, either to professional researchers or to members of the public.

Events, activities and preparation

The Science Ambassadors lead a range of different types of event to carry out the project's objectives, which include:

- talks / poster presentations;
- hands-on interactive workshops at public science festivals or teacher conferences;
- discussions and Q&A sessions;
- donating educational workshop equipment to educational centres, such as public observatories, and providing training for the local staff.

Events are planned around the interests and availability of the Ambassadors. There are two main types of venue for the events: (a) those based in scientific institutes, which are usually undertaken as part of a pre-planned science collaborative visit or conference; and (2) those based elsewhere, such as at science festivals, public observatories or teachers' conferences. For the latter we make use of the Ambassadors' own local contacts and the ESO Science Outreach Network (ESON) to find appropriate events or venues. In some cases, we are required to write a proposal to put on a workshop or stall at a science festival or conference. To date, these have always been successful, and we have noted considerable

Figure 1. ESO student (Garching), Aleksandra Hamanowicz, discussing the opportunities for women in astronomy at the *Galaktyka Kobiet* (Galaxy of Women) event in Poland.

enthusiasm for having ESO representation at these various events; for example, at *La fête de la science* in France and the *Associazione per l'Insegnamento della Fisica* (AIF) teacher's conference in Italy.

Several resources had to be prepared in early 2018 for the various activities. These materials, which are described below, have been created so that they can be continuously reused by ESO scientists during future activities. The Ambassadors were trained on site at ESO headquarters in how to use and deliver the different activities (although in one case last year, for a fellow based in Chile, it took place over a telecon).

Information posters and presentations

Posters and presentations have been developed that cover ESO scientific opportunities (for example, fellowships, studentships and internships) and ESO educational resources (for example, online images, movies and information). These have been translated into different languages, as necessary, for the individual events. They are available to be downloaded and printed by any ESO scientist visiting another institution or conference. Ambassadors have also accompanied their presentations with Q&A and discussion sessions where they can share their own knowledge and experience of the fellowships/studentships. For example, student Aleksandra Hamanowicz held a discussion session during an event to encourage young women into science in Poland (see Figure 1) and fellow Chris Harrison had a discussion about ESO research opportunities with students and postdoctoral researchers at Manchester University.

Hands-on and interactive educational workshops

Workshops developed by the ESO Supernova staff (in collaboration with Haus der Astronomie[2] in Heidelberg) were presented at various public science festivals, as well as to teachers. The Ambassadors also constructed and donated several workshop kits in the places that they visited.

These workshops are:

a. Telescope designs: This workshop uses a series of lenses, mirrors, light-emitting diodes and a "laser cannon" to showcase how refracting and reflecting telescopes work (see Figure 2). The Ambassadors also use this activity to explain the different designs of various ESO telescopes.

b. ELT and segmented mirrors: This workshop uses a series of lasers and small mirrors (with "actuator" screws on the back) to demonstrate how a large mirror can be made from several individual segments (see Figure 3). It also shows how light can be directed to different focus points in a telescope. The Ambassadors use this activity to describe the design of the ELT primary mirror.

c. Infrared pictures and exoplanet models: This activity uses webcams adapted to see at infrared wavelengths to look at models of Orion via which you can penetrate through dark clouds of gas and dust. In addition there are models based on real extrasolar planet systems (see Figure 4). This activity is used to explain the benefits of ESO instruments that can see in the infrared (for example, to study dusty nebulae and to directly image exoplanets).

Exoplanet Drawing activity and website

A series of exoplanet information planet cards were created with some key information about these planets (for example, the planet temperatures, sizes and masses). Participants in this activity (usually elementary school children), draw their own impressions of what these exoplanets might look like (see Figure 5). The drawings are uploaded to a dedicated website[3] that is maintained by the ESO Ambassadors. We also use the activity to explain the current status and future of understanding exoplanets and ESO's contribution to this research.

Figure 2. Hugo Messias, an ESO Fellow in Vitacura, presenting the telescopes workshop to visitors of the Lake Alqueva Observatory (OLA) in Portugal. The equipment is being kept at the observatory for use by future visitors.

Figure 3 (above). Teachers being trained by Chiara Circosta, ESO student in Garching, in how to use the ELT/segmented mirrors workshop.

Figure 4 (right). Students of a local school engaging with the public at the Celebrate Science festival in Durham (UK) to explain the benefits of using infrared light for astronomy.

Gavin Duthie Photography

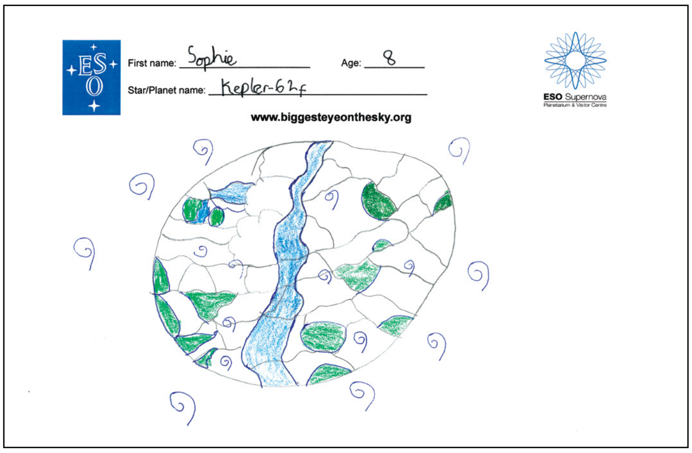
Other activities were also performed on an ad hoc basis. For example, during a teachers' conference, ESO Fellow Fabrizio Arrigoni Battaia carried out two Q&A sessions from the APEX control room to give the teachers a close-up view of observing at ESO facilities.

First year of activities and legacy

In 2018 the ESO Ambassadors carried out 20 activities across nine countries. The target countries in 2018 were ESO Member States and Chile. A full list of the events is provided in Table 1 and Figure 6 shows a breakdown of the different categories of audiences. Some notable figures: the Ambassadors engaged directly with ~ 6000 people; 524 different exoplanet drawings were uploaded live onto the project website[3]. It is also impressive that, in addition to the activities listed in Table 1, which were organised under the umbrella of ESO Science Ambassadors, ESO Fellows and students continued to organise their own additional public engagement events in parallel to this project.

Throughout the project, feedback was collected from the participants of the activities; this was overwhelmingly positive. For example: a participant at the Manchester Science Festival said, "Wow, (the Ambassadors) really opened up the world of telescopes for the kids"; one of the school students who helped the Ambassadors deliver activities said, "The brilliant activities I helped to carry out for ESO have helped me to find real world applications for the science I have learnt at school" and an undergraduate student, after speaking to one of the current ESO PhD students simply said, "I want to work in ESO!". In several cases the Ambassadors were invited to return the following year to carry out activities again. Of particular note were the organisers of *La fête de la science* who asked the ESO Science Ambassadors to return in 2019 as part of their bid to secure funding from the relevant French Ministry.

The Science Ambassador project aims to create a legacy so that the engagement with ESO is not limited to one-off events. In 2018, this included the manufacture and delivery of ESO Supernova workshops to Vitacura and the donation of these workshops to four different educational centres across Europe. Furthermore, around 200 local teachers or student ambassadors were trained to carry on delivering our messages about the



First name: Sophie
Age: 8
Star/Planet name: Kepler-62f

Figure 5. An example of an artist's impression of an exoplanet system drawn by one of our young participants. Similar artists' impressions can be found on the project website[3].

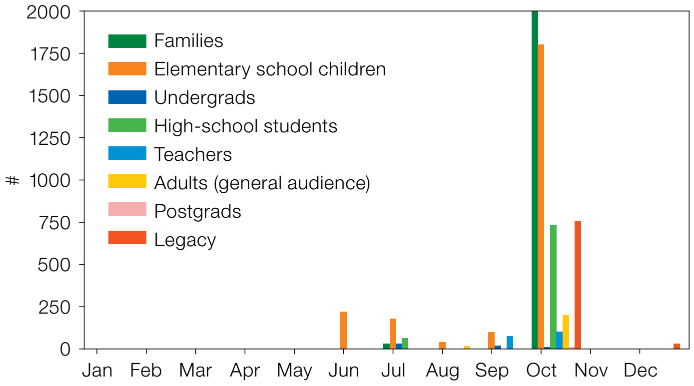


Figure 6. People engaging in activities led by ESO Science Ambassadors during 2018 divided by category (as explained in the legend). In red we highlight the number of people contacting the ESO Ambassadors after the events (for example, visits to the website, teacher's asking us to organise trainings in 2019, etc.).

ESO mission, long after the Ambassadors had left. The project website also enables members of the public to interact after the Ambassadors have left and provides a portal to the main ESO website.

Next steps

The Science Ambassador project is continuing into 2019. This has been possible thanks to careful handling of the initial funds from the SSDF. For example, when activities are carried out alongside existing science trips the overall cost to ESO is low. Furthermore, additional funds have been obtained by the ESO Fellows. In particular, funds were awarded by the International Astronomical Union as part of an IAU100 project so that activities could be carried out in a few non-ESO member countries: Croatia, Bulgaria, Hungary, Ukraine and Slovakia. The Ambassadors also plan to work with local schools in Ethiopia as part of activities related to IAU Symposium 356, which takes place in Addis Ababa in October.

To date, the team of Ambassadors has consisted of 19 ESO Fellows and students. These Ambassadors have been supported by an additional 38 scientists, school students or teachers who were recruited to help with presenting the activities locally. An additional 19 ESO staff, fellows, students and interns have also been involved in the project by providing various levels of support, for example by developing activities, translating documents, or assisting with organisational aspects.

Based on the resources that have been developed and the experience and knowledge already gained (for example, how to be involved in various science festivals), we foresee that Science Ambassador activities should be able to continue well into the future.

The ESO Science Ambassador project has been a fulfilling and gratifying experience. It has really highlighted the wonderful team spirit between ESO students

Table 1. Events and activities of ESO Science Ambassadors in 2018.

Country	Month	Event	Activities
Portugal	June	Noites do Observatório, Navy Planetarium	Public talk: *Um Universo com ALMA* and stargazing
Spain	July	XIII Biannual Meeting of the Spanish Astronomical Society	Poster on "ESO Opportunities for Early-Career Scientists"
Portugal	July	Lunar Eclipse event, Lake Alqueva Observatory (OLA)	Public talk. ESO Supernova workshops, presented and then donated.
Portugal	July	*Ser Cientista* (To be a Scientist)	Workshop for high-school students. ESO Supernova workshops in action.
France	July	*Soirée étoilée avec Toulx-et-possible*	Public talk on ESO's facilities: emphasis on ELT as mirror segments being built close by.
Italy	August	*A spasso tra le stelle* (for people with disabilities)	Mix of interactive lectures, videos, activities, exoplanet artists' impressions
Poland	September	*Galaktyka Kobiet* (Galaxy of Women)	Public talk on opportunities for women in astronomy, Q&A session
Poland	September	Physics teacher conference	Teacher training, advertisement of the ESO Supernova materials
Poland	September	Nationwide conference of undergraduate astronomy students	Public talk & poster about ESO and possibilities for early-career scientists at ESO
France	October	Festival Atmosphere (*La fête de la science*)	ESO Supernova workshops and exoplanet artists' impressions for schools and the general public
UK	October	Durham Science Ambassadors training session	Training and donation of ESO Supernova workshop equipment for teachers and pupils
UK	October	Celebrate Science Festival, Durham	ESO Supernova workshops and exoplanet artists' impressions for the general public
UK	October	Durham University	Q&A session for early-career researchers
UK	October	Manchester Science Festival, Manchester	ESO Supernova workshops and exoplanet artists' impressions for the general public
UK	October	Manchester University	Q&A session for early-career researchers
Italy	October	*57 Congresso Nazionale Associazione per l'Insegnamento della Fisica* (AIF)	Workshops for teachers on the ESO Supernova workshops. Q &A sessions with ESO Fellow observing at the APEX telescope.
Netherlands	December	Leiden Old Observatory	Donation of ESO Supernova workshop equipment.
Chile	December	ESO	Delivery of ESO Supernova workshop equipment.
Czech Republic	December	Astronomical Institute in Ondrejo and University in Brno	Talks and Q&A sessions for early-career researchers.
Poland	December	Almukantarat Astronomy Club	Donation of ESO Supernova workshop equipment.

and Fellows and the fantastic support from the wider ESO staff. The Ambassadors noted in particular how they enjoyed engaging with people from their own countries and observing how inspired they were by the ELT project. They also report how rewarding it has been to showcase the amazing resources of the ESO Supernova, and to help search for the next generation of ESO Fellows and students. We believe that a positive link with society is fundamental for the development of increasingly challenging astronomical programmes — we hope that the ESO Science Ambassador project will continue to achieve this for years to come.

Acknowledgements

The ESO Science Ambassador project is grateful for financial support from ESO's SSDF, SPIE[4], the IAU and the French Ministry for Culture and Education. The project is only possible thanks to the tremendous efforts of the ESO students and Fellows (both current and former alumni) who have acted as Science Ambassadors. To date, these are: Richard Anderson; Fabrizio Arrigoni Battaia; Barnabás Barna; Chiara Circosta; Jesús M. Corral-Santana; Jérémy Fensch; Aleksandra Hamanowicz; Miranda Jarvis; Tereza Jerabkova; Chris Harrison; Rosita Kokotanekova; Kateryna Kravchenko; Dinko Milakovic; Hugo Messias; Stephen Molyneux; Annagrazia Puglisi; Miguel Querejeta; Jan Scholtz and Anita Zanella.

The Science Ambassadors have also been supported in their activities by Simon Borgniet (Meudon Observatory), Lorraine Coghill (Durham University), Tracy Garratt (Hertfordshire University), Lucy Moorcraft (TUM), Alasdair Thomson (Manchester University), Kate Wetherell (Manchester University), and 32 students and teachers from the following UK Schools: Wolsingham School; St Bede's Catholic School and Sixth Form College; Longfield Academy; and St John's Catholic School.

A lot of support with developing materials, translating documents and planning events has come from the following ESO Interns, current and past students and fellows, and staff: Tania Johnston; Wolfgang Vieser; Mylene Andre; Stella-Maria Chasiotis-Klingner; Anne-Laure Cheffot; Giuliana Cosentino; Romain Lucchesi; Mariya Lyubenova; Carlo Felice Manara; Sara Mancino; Anna Miotello; Juliette Ortet; Elizabeth Russell; Saskia Schutt; Nicole Shearer; Nelma Silva; Giustina Vietri; Sebastian Wassill; and Alex Weiss. Finally, we warmly thank the ESON members who helped plan events and Jasmin Patel for help with coding and setting up the project website.

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GRAVITY Collaboration et al. 2018, A&A, 615, L15
Smartt, S. et al. 2017, Nature, 551, 75

Links

[1] The ESO Supernova Visitor Centre and Planetarium: https://supernova.eso.org/
[2] Haus der Astronomie: http://www.haus-der-astronomie.de
[3] The ESO Science Ambassador website: https://www.biggesteyeonthesky.org
[4] The webpage for the International Society for Optics and Photonics, SPIE: https://spie.org

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Fellows at ESO

Jesús Corral-Santana

Jesús Corral-Santana

Like many of my colleagues, my love for astronomy began when I was a child. In my case, it really was a vocational calling. I do not remember the first time I started to think about it, but I do remember asking my parents about astronomy and the possibility of going out during the night to observe the stars. I am originally from the Canary Islands where there is a strong astronomical community thanks to the good quality of the skies. For that reason, there was a lot of information in the local media about new discoveries and scientific results produced with the telescopes installed there.

I remember watching a series of documentary tapes released by a local newspaper and produced by the Instituto de Astrofísica de Canarias (IAC) about astronomy and being fascinated by all the things I did not know (including planetary nebulae, clusters, black holes). I specifically remember the tape where they talked about the first dynamical confirmation of the first black hole ever found by Jorge Casares — at that time a PhD student at the IAC.

During summer breaks, I used to visit my grandmother in Madrid and ask her or my aunt to take me to the planetarium. That was simply awesome for a 10-ish year old kid; I was fascinated by the shows while my aunt snored next to me. I could not understand why she was not thrilled about the show! For me, every summer visit to Madrid meant a visit to the planetarium and a suitcase full of posters and merchandising.

Back at home, I started to fill my bedroom with all of that stuff: a luminescent clock which had the visible side of the

Moon labelled with the names of all the craters and plains (*mares*); posters with all the constellations visible from the northern hemisphere; and a lot of fluorescent star and planet-shape stickers with which I covered the walls and ceiling of my bedroom, creating my own illuminated sky during the night.

During my whole childhood I grew up reading about astronomy in books and watching documentaries. One Christmas, I got a telescope and that changed everything! We could not afford to buy a car so I could not go far with it but I will never forget the first time I saw the Moon through that telescope. From that moment, I knew what I wanted to do in my life.

I read about all the steps required to become an astronomer and started to take decisions. There was no astronomy or physics at the local university but there was a good faculty of physics on the other main island of the archipelago. My parents and relatives supported me at every step, and when I was 17, I took my suitcases and moved alone from Gran Canaria to Tenerife.

It was not easy. We did not have the economic resources to sustain my adventure of living abroad so I had to work and get grants in order to pay for my university years. But it was totally worth it. During my final year I applied for the “resident” PhD grant at the IAC and I was one of the selected candidates. That was a major achievement for me because of the large number of applicants and the reputation of that grant.

I started to work with Jorge Casares and Ignacio González on X-ray binaries, interactive binary systems formed by a black hole which is accreting material from a companion star. The project was exciting and my supervisors were great. From the very beginning, one of our main goals was to find more systems harbouring black holes. At that point, only 17 had been confirmed after more than 50 years of X-ray astronomy! Transient X-ray binaries are detected by X-ray satellites when they go into outburst, but to obtain the dynamical solution of the system, we need to observe them at optical and infrared wavelengths.

During my PhD we were able to identify two new systems containing black holes, increasing the number of systems known. One of the major handicaps in this field is the difficulty of detecting new systems. So far this is only possible when they enter into outburst. However, this happens randomly across the sky and in time, so it is not very efficient. Thus, our understanding of the properties of these sources as a whole is very limited. On the other hand, dynamical confirmation requires the system to be in quiescence, but this is also when the system is fainter. Since the vast majority of sources are locatedin the Galactic plane, the reddening added to the faintness of the low-mass star companion (which dominates the optical/infrared spectrum in quiescence) is also a limitation in the field of transient X-ray binaries.

During my PhD, we addressed these two issues, trying to develop new techniques that can help us unveil new systems, and using current instrumentation to confirm the nature of already known sources. Thus, I spent a significant fraction of my PhD observing on La Palma (Canary Islands), South Africa and Chile, where I learned a lot about carrying out observations. By the end of my PhD I had nearly 120 nights of observational experience behind me, using all kinds of telescopes, instruments and observing modes.

When I finished my PhD I started to look for postdoc positions everywhere; Chile was at the very top of my list because of the large number of observatories hosted in the country, and the excellent conditions for observational astronomy. During my search for a postdoc, I met Franz Bauer from the Pontificia Universidad Católica de Chile (PUC) who suggested that I apply for a Fondecyt Postdoctoral fellowship, which we got in 2013. This led to me packing again, this time for a larger jump over the Atlantic.

I was at PUC for almost three years before joining ESO as a fellow, with duties in Paranal, and where I have now been working for more than two years. Coming to ESO was an easy transition for me — from the very beginning I felt totally integrated at ESO. I started my training at UT1, becoming the *K*-band Multi-Object Spectrograph (KMOS) fellow, but also taking care of the other two instruments mounted at the telescope, the Nasmyth Adaptive Optics CONICA System (NACO) and the FOcal Reducer/low dispersion Spectrograph 2 (FORS2). More recently, I extended my duties to support UT2 as the X-shooter fellow, also taking care of operations on the Fibre Large Array Multi Element Spectrograph (FLAMES) and the Ultraviolet and Visual Echelle Spectrograph (UVES).

During these years I have learnt a lot. Although I had considerable observational experience as an astronomer thanks to my work on surveys, the way of carrying out operations at Paranal is completely different. I love working at the observatory; I am always learning something new and there are always a lot of new things to do and problems to solve. I find it challenging and stimulating and we never get bored. I also like the working environment; it is great working with the team of engineers, scientists and operators during a shift which could last as long as 14 days! We get the opportunity to be involved in small projects to improve the efficiency of the instruments and keep in touch with the day-to-day activities.

In October I will finish my third year as an ESO Fellow and will conclude my duties in Paranal. I still do not know where I will be in a year’s time, but I am pretty sure that I will miss Paranal and my colleagues at ESO.

Claudia Agliozzo

I grew up in a town at the foot of Mount Etna in Sicily, Italy. When I was 11 years old, I joined the Scouts and we used to go camping. During the hot Sicilian summers there can be a few nights when the Tramontane wind clears away the hot sultry air and brings respite. From the Nebrodi mountains, far from light pollution, you get the chance to see the Milky Way. My friends designated me the astronomer in the group, and that became one of my specialities as a scout.

Those were also the years after the Maastricht Treaty. I wrote an essay about it for the final exam at middle school; I had absorbed all the enthusiastic feelings

Claudia Agliozzo

of my parents and my teachers. I would have been very excited to hear that one day I would become an astronomer and work in an international organisation such as ESO.

Later, I attended a classical lyceum, with many hours of literature, Latin and Ancient Greek, but my favourite class was that of my enthusiastic physics teacher. After my school years, with no hesitation at all, I signed up to study Physics at the University of Catania.

During my undergraduate studies I grew interested in different topics in physics, but by far my favourite course was the one on radio astronomy, held at Catania's INAF observatory by Corrado Trigilio. I was motivated to learn radio interferometry while working on my first research project for my master degree thesis — a study of the radio emission of the rapidly evolving protoplanetary nebula CRL618 using data from the Karl G. Jansky Very Large Array. I presented this work at the Young European Radio Astronomy Conference in Portugal. This was the first time I met colleagues from different parts of the world, with different astrophysical interests and backgrounds. I understood that this was another attractive aspect of scientific research, and at that point I decided to gain further experience in research. I enrolled in the PhD programme at the University of Catania and continued to work with the radio astronomy team, this time on a study at radio and infrared wavelengths of the ejecta of luminous blue variable stars (LBVs) in our Galaxy, supervised by Grazia Umana. These are blue supergiant stars that experience enigmatic violent episodes of mass loss during the final stages of their evolution, before core-collapse and their subsequent supernova explosions.

During the first year of my PhD programme I spent some months at Caltech in California, where I learned to analyse data from infrared space telescopes for my study and also worked on another project involving Australia Telescope Compact Array (ATCA) data of a nearby star forming region.

On returning to Italy, I had become experienced with ATCA data and wished to expand my study of LBVs to lower metallicity environments, similar to the early Universe. The best laboratory for this study is the Magellanic Clouds, which can only be observed from the southern hemisphere, and the only interferometer available to observe them at that time was the ATCA. My first observations were truly an experiment and finding LBV sources in the data was very exciting.

I defended my PhD thesis in 2013. My first postdoc brought me to Chile. I joined the Supernova team at Universidad Andres Bello (UNAB) in Santiago and I was encouraged by my advisor, Giuliano Pignata, to follow up my study of Magellanic LBVs with ALMA to address their role as dust producers at low metallicities. For the first time I went to Narrabri in Australia to perform observations of my favourite sources myself.

At that observing site, you get to operate six radio telescopes, collect the data and bring them home. Meanwhile, I got observing time with ALMA, which I wanted to visit. I am grateful to Becky Vega and Richard Hills for having organised a special tour for me of the ALMA antennas and the Operations Support Facility; it was here that I got a taste of working life in a big observatory.

At the end of the same year I was awarded a three-year Fondecyt fellowship and continued to work at UNAB. I was involved in observations for supernova searches and follow-up programmes, including the CHilean Automatic Supernova sEarch (CHASE) and the Public ESO Spectroscopic Survey for Transient Objects (PESSTO), during which I had the opportunity to carry out observations with telescopes at Cerro Tololo and with the New Technology Telescope at La Silla. Visiting the ESO facilities was my dream as a kid and I felt very lucky to have fulfilled that.

I particularly enjoyed carrying out observations, both for myself and for others, and what I wished to experience next was working in a big facility such as ALMA. At the conclusion of the four-year period of my position at UNAB I applied for an ESO Fellowship in Chile. I joined ESO as a fellow at the end of 2017 and did my duties at ALMA. Here there are 10 times as many antennas as at ATCA and substantial team effort is necessary to make the observations possible. My most common role is "Astronomer on Duty", which involves participating in the science operations at the OSF. I have also coordinated a large observatory project with the 7-metre and total power antennas, working on evaluating stars as potential high frequency calibrators for ALMA.

I recently moved to ESO in Garching for the remainder of my fellowship, and I work with the ALMA Regional Centre to support the European ALMA community. Both ESO offices in Garching and in Vitacura attract scientists from all over the globe for collaboration and on observing trips. Every day is an opportunity to learn more science and meet more people. As a fellow, you get the opportunity to benefit from different trainings to improve your professional skills and you can always find somebody eager to give you advice, both for your work and your career. I feel particularly privileged to be spending my time at the ESO offices and facilities.

Richard Anderson

In hindsight, there were clear precursors for my later career as a professional astronomer, such as trying to photograph Comet Hale-Bopp with my father's film SLR camera when I was a kid, or my interest in *A Brief History of Time* soon thereafter. However, the adolescent me was much more interested in acting than academia, even though I chose to enroll in a physics undergraduate degree at Augsburg University for the presumably more stable job prospects. Joking aside, my path to becoming a professional researcher at ESO, the world's most productive ground-based astronomical observatory, has been an exhilarating journey and I am grateful for the amazing opportunities I was offered, the profound experiences I had, and the wonderful people I interacted with along the way. I love being an astrophysicist.

Moving to Lund, Sweden as an ERASMUS exchange student was perhaps the best gut decision I ever made. Lund was transformative for my development thanks to excellent instructors, highly motivated peers, and the life experience of leaving my comfort zone. After the exchange, I moved to Göttingen, Germany, where I pursued interests in both high-energy particle physics and astrophysics and seized opportunities for research internships at DESY in Zeuthen, Germany, at ASIAA in Taipei, Taiwan, and the Sudbury Neutrino Observatory group at Carleton University in Ottawa, Canada. In a dream, I eventually realised that astrophysics was my favorite subject, and this was cemented by seeing Saturn's rings through the University's 50-cm rooftop telescope. Having found my academic *raison d'être*, I started on my year-long *Diplomarbeit* to measure stellar magnetic fields in Ansgar Reiners' Emmy Noether research group.

For my PhD I moved to Geneva Observatory in Switzerland, where I specialised in the astrophysics of classical Cepheid variable stars, under the supervision of Laurent Eyer and Nami Mowlavi in the group that leads the variability processing effort for the ESA space mission Gaia (launched 3 days after my thesis defense). As a member of Gaia's Data Processing and Analysis Consortium I was able to contribute to this huge project while conducting the majority of my research in smaller collaborations. Connecting with members of different research groups across Geneva observatory, I soon collaborated with stellar evolution experts (notably Georges Meynet and Corinne Charbonnel) on the effects of rotation on the evolution of Cepheids and learned about high-precision radial velocity measurements from the Geneva exoplanet team.

Following my interest in precision radial velocities, I initiated the Geneva Cepheid Radial Velocity Survey (GE-CeRVS), which I am currently working to complete. Since 2011, GE-CeRVS has gathered more than 19 000 observations using two "small" (1.2-metre) telescopes, one in each hemisphere, namely the Mercator on La Palma and the Euler at ESO's La Silla Observatory. Of course, I gathered a large fraction of these observations myself over the course of 264 unforgettable nights. However, GE-CeRVS would not have been possible without the invaluable contributions of numerous colleagues and friends made who helped out with observations, provided technical assistance, and allocated telescope time or other resources (Thank you all!). Thanks to an unprecedented combination of precision (as good as 2 m s^{-1}), dense phase coverage, and multi-year baselines of more than 270 Milky Way Cepheids, GE-CeRVS data have uncovered new aspects of the variability of Cepheids and provide unique insights into stellar pulsations and distance measurements.

GE-CeRVS also acted as a catalyser for establishing a fruitful and enriching collaboration with interferometry experts (notably Pierre Kervella, Alexandre Gallenne, and Antoine Mérand). With them I led two successful Very Large Telescope Interferometer proposals for the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER), which took me to ESO's Paranal observatory as a visiting astronomer. What a privilege to have so much freedom to explore and follow my curiosity!

In my current functional work as an ESO Fellow, I continue to pursue my interest in high-precision spectroscopy by contributing to the data reduction pipeline development of the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) — the most stable spectrograph ever built. ESPRESSO will be a game changer in the search for, and characterisation of, rocky exoplanets, while bringing us closer to directly measuring the expansion of the Universe via the Sandage-Loeb test.

In 2014, I secured a postdoctoral fellowship from the Swiss National Science Foundation to work with Nobel laureate Adam Riess and members of the team working on the Supernovae and H_0 for the dark energy Equation of State (SH0ES) programme in Baltimore, USA. Those three years were amazing, and I am particularly grateful to Stefano Casertano, who quickly became a friend and mentor to me. At Johns Hopkins University, I began shifting my focus from better understanding the stellar physics

Richard Anderson

of Cepheids to improving the accuracy of Cepheid-related distance measurements. Specifically, I collaborated with Adam and Stefano to quantify parallax errors due to orbital motion and bias produced by stars physically associated with Cepheids.

Meanwhile, the SH0ES team significantly improved the accuracy of the extragalactic distance ladder and established an intriguing discord between late- and early-Universe values of Hubble's constant, H_0. This so-called "Hubble tension" — which now figures at a significance of 4.4 σ — leads to the exciting possibility of an imminent breakthrough in fundamental physics, as the difference between late- and early-Universe H_0 values suggests that the ΛCDM Concordance Cosmological Model may be incomplete. However, before new physics can be credibly invoked to resolve the Hubble tension, known and unknown error sources must be critically assessed and further reduced, and independent, high-accuracy (1–2%) H_0 measurements pursued.

I am highly motivated to further elucidate the Hubble tension via my experience in the stellar astrophysics of Cepheids and the calibration of the cosmic distance ladder, and to this end I am currently working with Martino Romaniello and PhD candidate Sara Mancino to characterise the effect of chemical composition on Cepheids and the Leavitt law. Mentoring and advising graduate students has been a particularly rewarding experience for me, and I look forward to leading a research group of my own because this will allow me to continue pursuing my research ideas while improving the chances of contributing to a major breakthrough. In any case, I will surely have a blast trying!

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Gustav Andreas Tammann (1932–2019)

Bruno Leibundgut[1]

[1] ESO

Gustav Andreas Tammann died in January 2019, after a long and successful astronomical career. He made seminal contributions to extragalactic astrophysics and cosmology and is best known for his work to determine the Hubble constant and the use of supernovae as cosmic distance indicators. For many years he was the leading extragalactic astronomer in Europe. Tammann also had a long association with ESO and was instrumental in convincing the Swiss government to join the Organisation in 1982.

After a degree from the University of Basel, Switzerland, Tammann spent time as a Research Associate at the Mount Wilson and Palomar Observatories in Pasadena, California. After his return to Europe he first held a professorship in Hamburg, and was then Director of the Astronomical Institute in Basel from 1977 until his retirement in 2002.

While in Pasadena, Tammann and Allan Sandage initiated a research programme resulting in a collaboration lasting over four decades, aimed at establishing the distance ladder and ultimately measuring the value of the Hubble constant. They carefully investigated every rung of the distance ladder until they reached distances in the Hubble flow to establish the current cosmic expansion rate. Tammann strongly advocated the use of supernovae as distance indicators and in other cosmological applications, for example, using time dilation to test general relativity. He was vindicated by the successful use of Type Ia supernovae to provide a reliable last rung into the Hubble flow, and ultimately to produce evidence for accelerated cosmic expansion. The exact value of the Hubble constant remains a matter of intense debate, but the local expansion rate is now almost exclusively measured by Type Ia supernovae (calibrated by Cepheid stars), the most accurate distance indicator available for cosmology to date.

Tammann received many distinctions, including the Karl-Schwarzschild Medaille of the Astronomische Gesellschaft, the Albert-Einstein-Medaille of the Einstein Gesellschaft Bern and the Tomalla-Preis by the Tomalla Foundation. He served as president of the Astronomische Gesellschaft from 1981 to 1984 and was an elected member of several academies.

Gustav Tammann had a close association with ESO for nearly 40 years. He was an ESO research associate from 1975 until 1993 (together with Philippe Véron, Franco Pacini and Jean-Pierre Swings), supported the then Director General Lodewijk Woltjer in scientific matters and helped build a science group at ESO headquarters. He worked with the Swiss government to enable the accession of Switzerland to ESO as the seventh Member State and served as the Swiss representative on the ESO Council from 1992 until 2002.

Personnel Movements

Arrivals (1 April–30 June 2019)

Europe

Booth, Michael Tucker (US)	Mechanical Engineer
Del Valle Izquierdo, Diego (CL)	Software Engineer
Gitton, Philippe, (FR)	Opto-Mechanical Engineer
Kammerer, Jens (DE)	Student
Kurian, Kshama Sara (IN)	Student
Mc Manmon, Conor (IE)	Software Engineer
Péroux, Céline (FR)	Astronomer/Instrument Project Scientist
Poci, Adriano (AU)	Student
Podgorski, Stanislaw (PL)	Software Engineer
Reinacher, Andreas (DE)	Control Engineer
Riffald Souza Breuer, Jean-Paul (DE)	Student
Sedaghat, Nima (IR)	Data Scientist (Deep Learning)
Shchekaturov, Pavel (RU)	Software Engineer
Szubiakowski, Piotr (PL)	Software Engineer
Würschinger, Wolfgang (DE)	Administrative Clerk

Chile

Cano, Raul (ES)	Knowledge Management Program Manager
De Luca, Giuseppe (VE)	Hospitality Operations Supervisor
Navarrete, Camila (CL)	Fellow

Departures (1 April–30 June 20199)

Europe

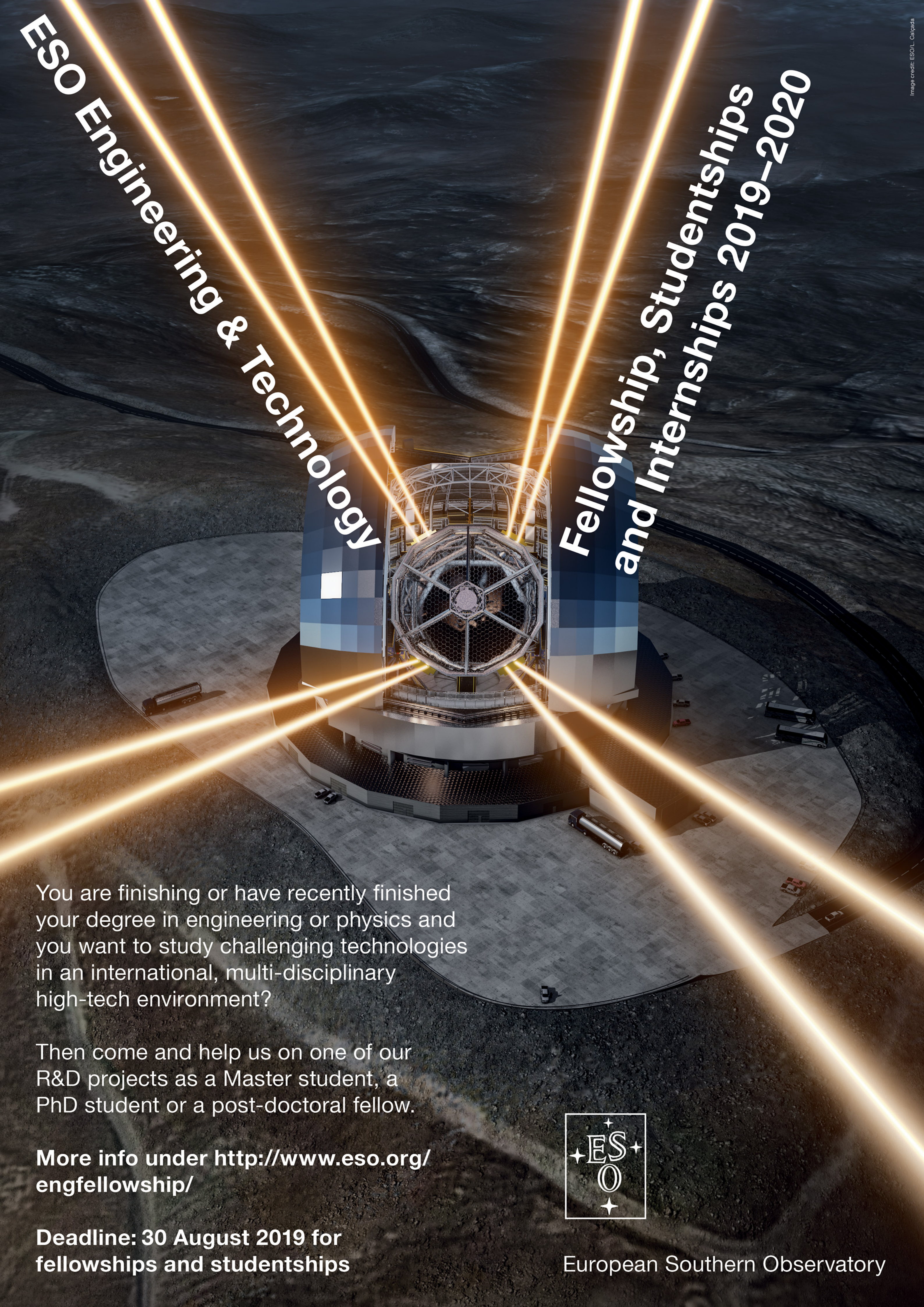
André, Mathias (FR)	Web & Advanced Projects Coordinator
Arumugam, Vinodiran (MY)	ALMA Pipeline Processing Analyst
Casali, Mark (IT)	Technology Development & Armazones Instrumentation Programme Manager
Eftekhari, Sara (IR)	Student
Gilmozzi, Roberto (IT)	Deputy Director of Programmes and Programme Scientist
Lizon à L'Allemand, Jean-Louis (FR)	Senior Technical Expert
Rupprecht, Gero (DE)	Quality Manager

Chile

Del Valle Izquierdo, Diego (CL)	Software Engineer
Haddad, Juan Pablo (CL)	Electronics Engineer
Ramírez, Andrés (CL)	Software Engineer
Wibowo, Ridlo (ID)	Student

A. Ghizzi Panizza/ESO

The VLT platform becomes reflective after a rainshower.



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