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Enhanced Data Discovery Services for the ESO Science Archive

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The archive of the La Silla Paranal Observatory is a powerful scientific resource for the ESO astronomical community. It stores both the raw data generated by all ESO instruments and selected processed data. We present new capabilities and user services that have recently been developed in order to enhance data discovery and usage in the face of the increasing volume and complexity of the archive holdings. Future plans to extend the new services to processed data from the Atacama Large Millimeter/submillimeter Array (ALMA) are also discussed.

Background and motivation

The ESO Science Archive[1] began operating in its current form in 1998, a few months ahead of the start of science operations of the Very Large Telescope, the VLT (see Pirenne et al., 1998). It is the operational, technical and science data archive of the La Silla Paranal Observatory (LPO). As such, it stores all of the raw data, including the ambient weather conditions, from the LPO, i.e., the telescopes at Paranal and La Silla, and the Atacama Pathfinder Experiment (APEX) antenna at Chajnantor. Also available through the archive are data from selected non-ESO instruments at La Silla, for example, the Gamma-Ray burst Optical/Near-infrared Detector (GROND), the Fibre-fed Extended Range Echelle Spectrograph (FEROS) and the Wide Field Imager (WFI). It also includes raw data for UKIDSS, the infrared deep sky survey using the wide-field camera WFCAM at the United Kingdom Infrared Telescope (UKIRT) in Hawaii. In addition, ESO hosts and operates the European copy of the ALMA Science Archive (Stoehr et al., 2017). The integration of archive services for LPO and ALMA data is discussed here.

Over the years, the archive has steadily grown into a powerful scientific resource for the ESO astronomical community. As processed data are routinely included, they can be used directly for scientific measurements, thus alleviating the need for users to carry out data processing on their own. An in-depth analysis of the archive usage and user community is presented in Romaniello et al. (2016).

The archive is populated with processed data through two channels. For the first channel, data-processing pipelines are run at ESO for selected instrument modes to generate products that are free from instrumental and atmospheric signatures and that have been calibrated. They cover virtually the entire data history of the corresponding instrument modes and are generated by automatic processing, with no knowledge of the associated science case. Checks are in place to identify quality issues with the products. The second channel involves data products that have been contributed by the community, which have been generated with processing schemes optimised to serve specific science cases. In most cases, they have already been used to derive published results (see Arnaboldi et al., 2014). These contributed datasets, which are validated via a joint effort between the providers and ESO before ingestion into the archive, often include advanced products like mosaiced images, source catalogues and spectra.

Thorough user documentation is also provided for all data releases, detailing the characteristics and limitations of each collection of processed data. This is particularly important, as it enables users to decide whether the data are suitable for their specific science goals. The systematic archive publication of such processed data dates back to 25 July 2011, with the first products produced by the Public Surveys conducted with the Visible and Infrared Survey Telescope for Astronomy (VISTA) infrared camera VIRCAM (Arnaboldi & Retzlaff, 2011). Processed data that were generated at ESO have been available since September 2013. An up-to-date overview of the released data is available online for contributed and pipeline processed data[2,3].

The number of users accessing processed data in the archive has grown steadily over time (Figure 1). At the current rate, an average of 2.2 new users are added every working day, with each user placing 11 requests on average. Given the growing popularity within the community, and the increasing volume and complexity of the archive holdings — and taking into account the recommendations of advisory bodies, such as the Users Committee, the Public Survey Panel, and the results of the community working group report on science data management (STC Report 580[4]) — it has become necessary to upgrade the ways in which users can access the ESO Science Archive in order to enhance data discovery and usage.

The trajectory of contemporary astronomical research increasingly involves multi-epoch, multi-messenger, multi-wavelength, multi-facility science, in which data are plentiful and varied. At the same time, data acquired from different facilities are becoming ever more complex, yet have to be combined in order to tackle increasingly challenging scientific questions. In this context, the role of science data archives is to lower the access threshold that separates researchers from acquiring and being able to work with the data that they are interested in. The average astronomer cannot be expected to be intimately familiar with the details of each archive and, even less, with the details of the instruments that produced the datasets concerned. The access layer to the data therefore has to be as self-explanatory as

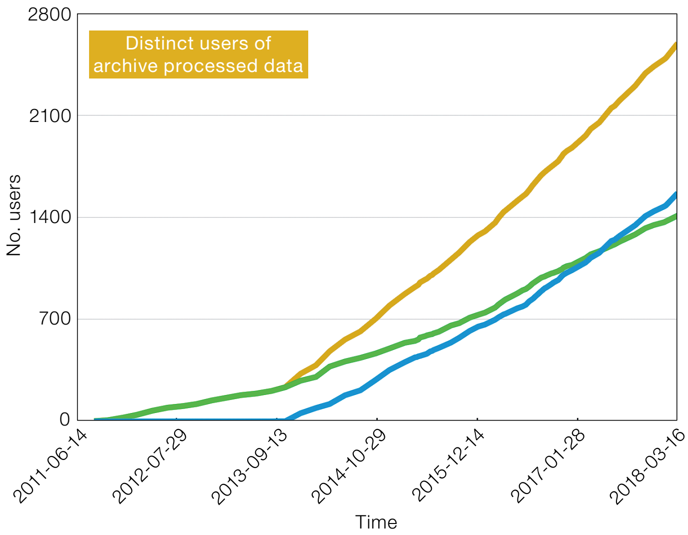


Figure 1. The growth of distinct users of processed data in the archive as a function of time. The green line displays access to products contributed by the community (deployed on 25 July 2011), the blue line shows access to products generated at ESO (deployed on 10 September 2013), and the orange line is for access to either type of products.

— Generated at ESO
— Contributed by the community
— Either one

possible so as to present the data in a user-friendly way, rather than couched in the technical terms used within the archive itself (for example, as calibrated fluxes and wavelengths, rather than detector counts, or an engineering description of the instrument setup).

Access points to the data

Different types of user interaction are supported:
- Interactive access: web pages through which users can browse and explore the assets with interactive, iterative queries. The results of such queries are presented in real time in various tabular and/or graphic forms, allowing an evaluation of the usefulness of the data which can then be selected for retrieval.
- Programmatic access: whereby users are able to formulate complex queries through their own programmes and scripts, obtain the list of matching assets, and retrieve them.
- Access by tools: whereby data are discovered, selected and accessed through tools normally developed by third parties, which are external to the web access channel. These tools often implement sophisticated data handling capabilities, such as TOPCAT[5] for catalogues, or Aladin[6] for images.

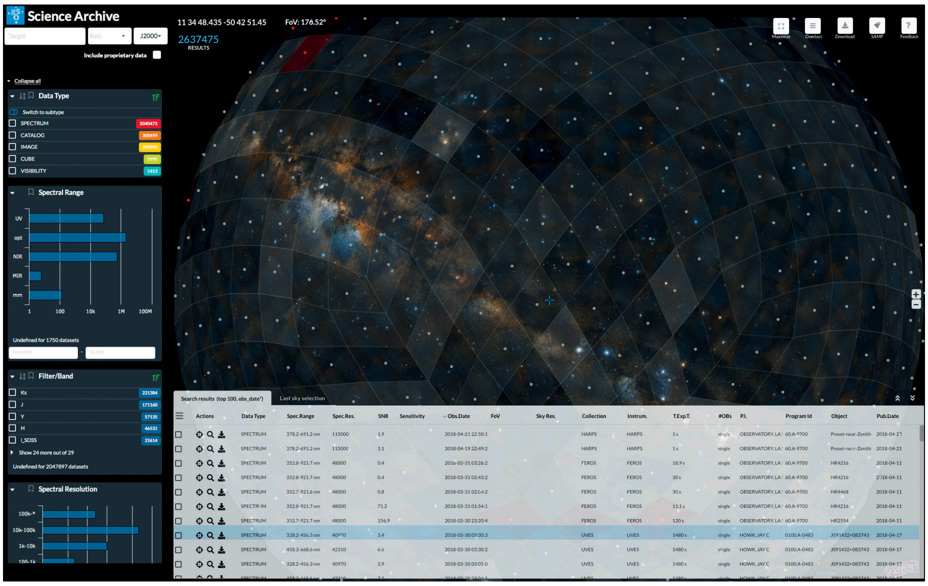
Furthermore, in order to fulfil the potential of multi-wavelength, multi-messenger science, ESO data need to be easily discoverable and handled so that they can be used together with datasets from other observatories and data centres. The natural framework for this is within the Virtual Observatory (VO); compatibility and interoperability with the VO is therefore a high-level goal for this project.

In this first release, processed data from the LPO are supported. Future plans include expanding the support to ALMA processed data and raw data from the LPO. It is planned that these new access points will gradually replace the current ones for La Silla Paranal data, while ALMA will keep maintaining a dedicated, separate access.

The ESO Archive Science Portal

The most immediate way to access the new archive services is through a web application, the ESO Archive Science Portal[7], using any recent version of the most popular internet browsers. A screenshot of its landing page is shown in Figure 2. The window is divided into three main sections: a sky view in which the content of the ESO archive is displayed together with background imagery such as the DSS; a table in which details of individual datasets are shown and from which further actions can be triggered, such as accessing previews; and a section in which query constraints can be specified, by explicitly entering them and/or by selecting values or ranges of values arranged in facets. Query results can be sent to suitable external applications for

Figure 2. The landing web page of the ESO Archive Science Portal. The celestial sphere is colour-coded according to the types of ESO data contained at each position (the sky viewer is CDS' AladinLite[6], the web version of Aladin). The entire content of the archive is presented through aggregations of 17 parameters, which can also be used to enter query constraints, in addition to querying by object coordinate or name, as resolved by the CDS's Sesame service[8]. In order to serve different use cases, they are a combination of physical characteristics of the data (e.g., signal-to-noise ratio, sensitivity, spectral range covered, spectral resolution), the observational setup (e.g. filter name, exposure time) and the ESO observing process (e.g. PI name, Programme ID).



further specialised analysis. To this end, the ESO Archive Science Portal communicates via the SAMP[9] protocol, which is supported by popular astronomical tools like TOPCAT and Aladin, enabling them to receive information easily.

Multi-dimensional faceted search

In order to serve a broad range of use cases, 18 query parameters are openly available. They are a combination of positional parameters (cone search around a given position on the sky), physical characteristics of the data (for example, signal-to-noise ratio, sensitivity, spectral range, spectral and spatial resolution), the observational setup (for example, filter name and exposure time), and the ESO observing process (for example, Principal Investigator [PI] name and Programme ID). Since many parameters are intrinsically interdependent, constraining one parameter typically restricts the meaningful range of one or more of the others. As a simple example, specifying a PI restricts the choices of Programme IDs to their programmes.

In order to cope with this, the query parameters and search results are grouped according to facets, so the user can easily be exposed to and navigate the multidimensional space of the archive. Wikipedia defines facets as follows[10]: “A faceted classification system classifies each information element along multiple explicit dimensions, called facets, enabling the classifications to be accessed and ordered in multiple ways rather than in a single, pre-determined, taxonomic order”. This concept may be familiar from most e-commerce sites. In practice, at any given time the user is presented with the available parameter space accounting for the previously specified constraints. In our simple example of specifying a PI name, the choices in the facet of the programme ID will be limited to the programmes by that PI.

Two additional features are offered to ease navigation. Where appropriate, entering the constraints is supported by auto-completion. Also, the possible values that a query parameter can take are grouped and presented as histograms or lists, as appropriate. In this way, the system communicates its content to users at all times, without the need for any previous knowledge. For example, as shown in Figure 3, it is immediately apparent that the archive contains data of several different types, including spectrum, catalogue, image, image cube and visibility (the counts for each of these categories are also provided). The equivalent information and grouping are available for all other search parameters.

With this approach, searches flexibly adapt to input from the users, guiding them through the content of the archive, rather than limiting them to a pre-defined set of possible paths.

Previews, hierarchical views and footprints

A preview is a lightweight, faithful representation of the actual data, which allows the user to evaluate their usefulness without transferring the full-size file(s). They are needed for a swift but in-depth assessment of the data, beyond the characterisation provided by the faceted query parameters described above.

Data exposed through the ESO Archive Science Portal display a great variety. For example, the range in images spans a few million to several hundred million pixels; in spectra it covers a few hundred to several hundred thousand spectral channels; and data cubes provide simultaneous 3D information. In terms of spatial extent, the ESO archive contains datasets that range from individual pointings to covering significant fractions of the celestial sphere — the whole hemisphere in the case of the VISTA Hemisphere Survey (VHS) public survey. This large spatial dynamic range is handled by adopting the Hierarchical Equal Area isoLatitude Pixelation (HEALpix) pixellation[11] of the celestial sphere (see Figure 3).

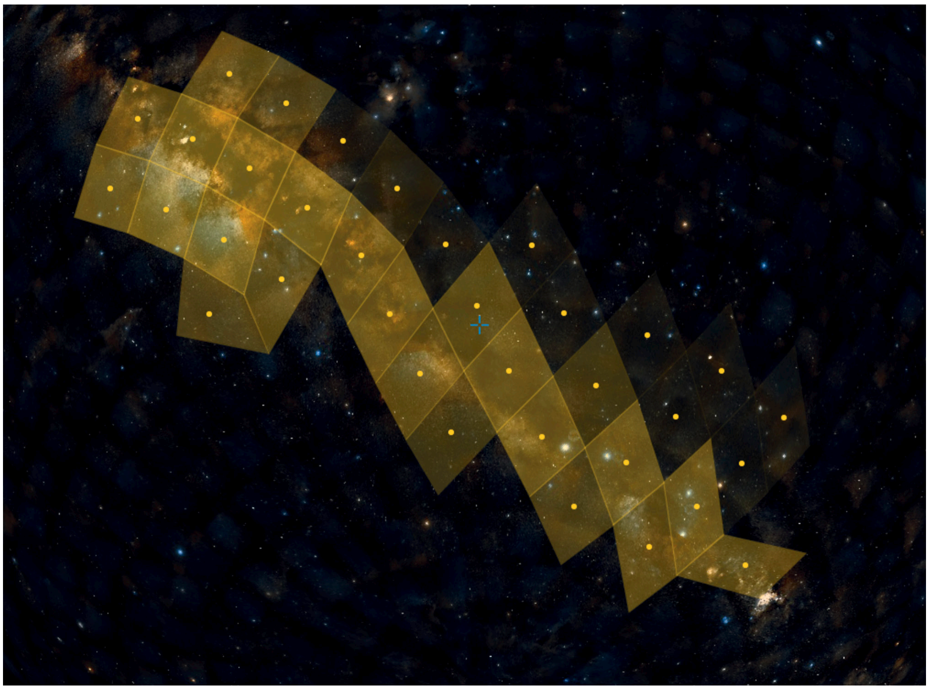


Figure 3. The all-sky search and rendering capabilities of the ESO Archive Science Portal make it easy to find and visualise data collections that span large areas of the sky. In the example above, the footprint of the VVV Public Survey covering 630 square degrees is shown on the all-sky DSS imagery. The level of transparency reflects the relative number of VVV images in the different locations on the sky.

Customised previews are offered for different data types, which include the possibility of user interaction (for example, zooming and panning) to navigate through the different spatial and spectral scales within the data. An example of a preview of a spectrum is shown in Figure 4. Image previews are rendered with a hierarchical tiling mechanism called Hierarchical Progressive Surveys (HiPS)[12], which adaptively provides the appropriate spatial scale at any given zoom level, resulting in a responsive and satisfactory user experience. An example is shown in Figure 5, in

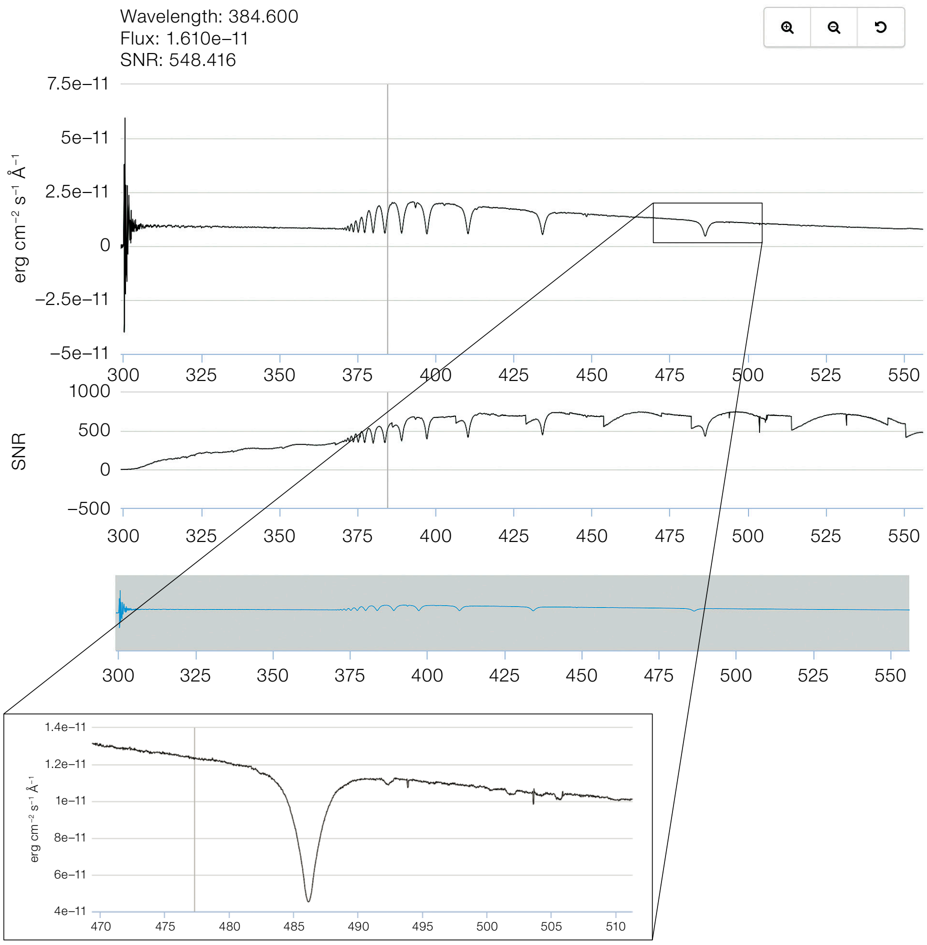


Figure 4. Example of a spectrum preview: the star Hip058859 as observed with the X-shooter instrument. Dynamic interactions are possible in order to evaluate the quality of the data and determine that they are fit for the intended purpose, e.g., by interactively zooming in on a spectral region of interest (inset).

which the preview of a tile from the VISTA Variables in The Via Lactea (VVV) Public Survey is superimposed on an image from the Digitized Sky Survey (DSS). On-sky footprints can be superimposed on an image of the celestial sphere to place the data in context and assist in browsing and selection (see Figure 6 for an example).

Direct database and Virtual Observatory access

The inherent limitation in the intuitive way that the web interface enables archive content to be discovered is that it is unsuited to more complex queries, such as those that include sequences with logical statements like “and”, “or” and “not”, or queries that join different sources of information. This restriction can be overcome by bypassing the web interface, thus providing direct access to the ESO database tables[13]. By adhering to widely recognised standards developed by the International Virtual Observatory Alliance (IVOA)[14], the ESO data can be queried alongside data from other observatories and data centres. This brings the ESO data into the appropriate general context of multi-wavelength, multi-messenger science.

Programmatic access

Users can specify their own custom queries via a standard service protocol using the IVOA’s Astronomical Data Query Language, ADQL[15]. The service

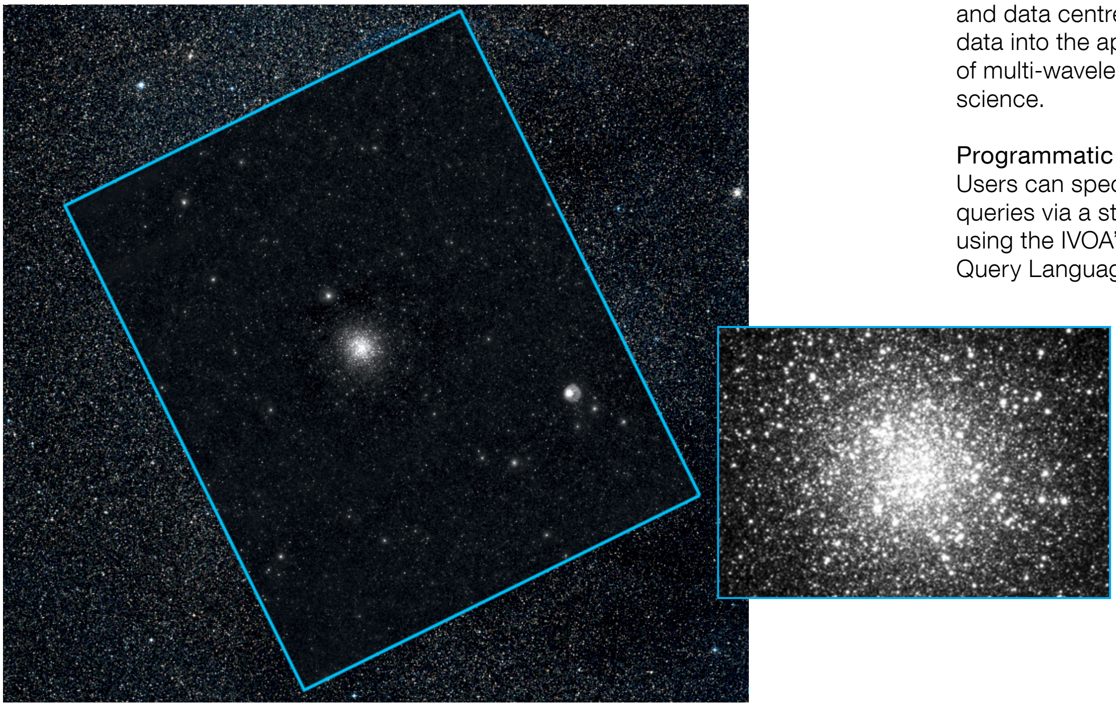


Figure 5. A preview of one tile from the VVV Public survey is shown superimposed on the backdrop of the DSS. The preview itself was generated using the HiPS mechanism and can be interacted with by zooming and panning on it. A full-resolution zoom on the inner-most regions of the stellar cluster in the tile is shown in the inset. Zooming in dynamically loads the appropriate spatial hierarchy, which provides for a responsive and satisfactory user experience.

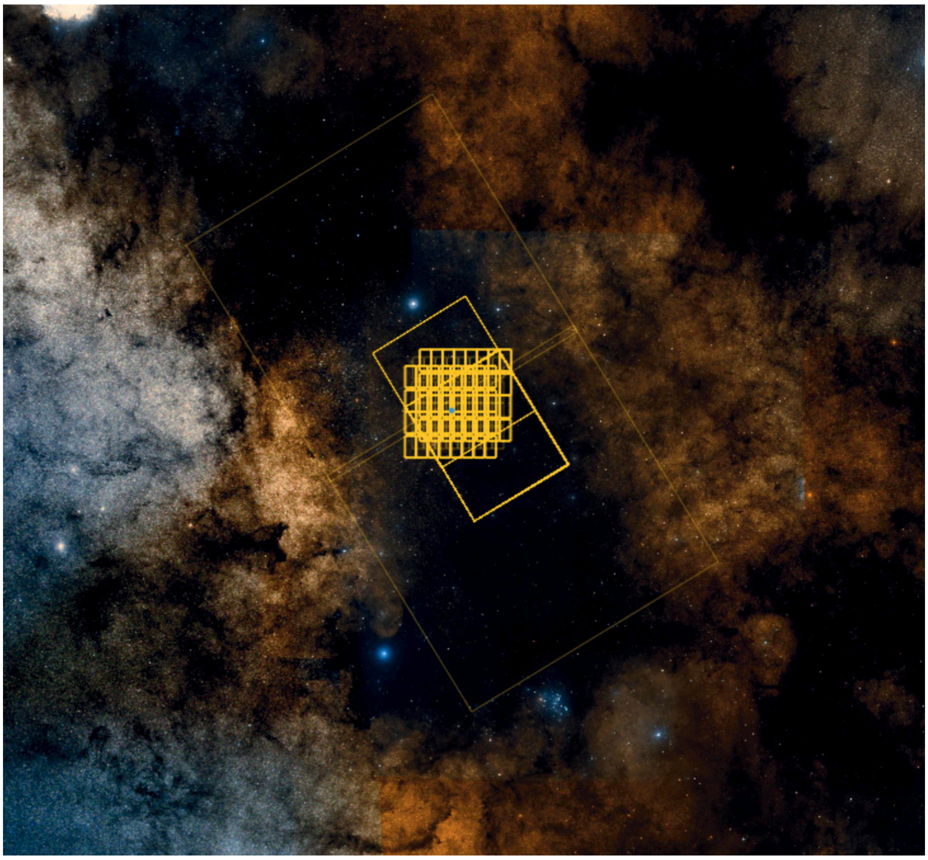


Figure 6. Examples of footprints of imaging data towards the Galactic Centre: VIRCAM data from the VVV Public Survey, OmegaCAM data from the VST Photometric Hα Survey of the Southern Galactic Plane and Bulge (VPHAS+ Public Survey), and APEXBOL data from the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL Large Programme). Background imagery is from the DSS.

protocol used to accept the queries and return the results is the Tabular Access Protocol (TAP)[16] of the VO. Existing public domain software libraries providing TAP-client capabilities can be used to implement full programmatic access to the ESO science archive (for example, astroquery[17], pyvo[18], STILTS[19], to name but a few).

The ability to access the archive with scripts allows users to efficiently and reliably run long and/or repetitive sequences of queries, such as those needed to quickly access data from monitoring or other time-critical programmes. The capabilities of ADQL allow queries on the spatial footprints of the processed data. Some examples of the types of queries include searching in a cone, a more sophisticated "point in footprint" query (for example, if a user wishes to find the progenitor of a supernova that had previously been imaged in one of the 16 non-contiguous VIRCAM detectors), and the ability to find images or source tables in different filter bands whose footprints overlap (enabling the selection of processed data for colour-magnitude studies).

The tables exposed in this first release of the ESOtap[20] service are the IVOA Obscore[21] which fully characterises the processed products, and ESO tables describing the LPO and Chajnantor raw observations and atmospheric conditions[22,23,24] (for example, seeing, precipitable water vapour, isoplanatic angle). A second TAP server[25] is available to query the content of more than five billion records of high-level science catalogue data. In order to optimise the response for such a large pool of data, the spatial searches supported in this first release are limited to cones. Extensive documentation is provided in terms of practical examples, which are intended to provide templates for users to customise and adapt to their specific needs[26].

A VO data link service[27] has also been implemented. It provides access to scientific data, their ancillary files (for example, weight maps), previews and data documentation. It also lists information related to provenance (such as the data files that were used to derive these products, and any data that were produced using these files). The VO Simple Spectral Access (SSA) service[28] provides easy browsing and access capabilities for the 1D spectroscopic data.

Tool access

The same basic infrastructure behind programmatic access allows users to browse the ESO archive from VO-aware applications. This enables users to discover and access ESO data through stand-alone tools, which have powerful generic and/or specific capabilities that cannot be implemented in a general interface. Examples of such external tools include TOPCAT and Aladin, as well as tools like SPLAT-VO and other clients that implement the Simple Spectral Access Protocol (SSAP) of the VO. To achieve this, all ESO VO-compliant data services are published in the IVOA Registries, allowing VO tools to discover them.

The Archive Community Forum

Finally, open communication with users is crucial in order to collect precious feedback and exchange individual experiences. To this end, the ESO Archive Community Forum[29] is available for users to post comments, questions and suggestions addressed to ESO, or intended for the community at large. Posts are moderated by ESO and, provided they meet basic standards of relevance and etiquette, are made openly visible.

Acknowledgements

The first step towards providing this comprehensive suite of services involves the curation of archive assets, which is an integral part of the Phase 3 process (Arnaboldi et al., 2014). We would like to warmly thank the PIs and their teams who have engaged with us in this process, which has greatly enhanced the value of the ESO Science Archive.

We would like to gratefully acknowledge the very fruitful collaboration with Centre de Données astronomiques de Strasbourg (CDS). This research has made use of the Aladin sky atlas developed at CDS, Strasbourg Observatory, France (Bonnarel et al., 2000, Boch & Fernique, 2014).

Many crucial aspects of the work presented here would have not been possible without the results of the sustained, distributed efforts of the VO community. The following IVOA standards were used: ADQL v2.0, DataLink v1.0, ObsCore v1.1, SSAP v1.1, TAP v1.0, UWS v1.1[30], DALI v1.1[31], SAMP v1.3.

We have made use of the taplib library[32] by Grégory Mantelet (Astronomisches Rechen Institut, Heidelberg), which is a collection of Java libraries implementing ADQL, TAP, and UWS. Grégory's support is gratefully acknowledged. The ESO implementation of taplib[33], providing additional support for the specific Microsoft-SQL Server geographical datatypes and functions, and the implementation of the SSA protocol[34], are made available to the community via github.

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Stoehr, F. et al. 2017, The Messenger, 167, 2
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Links

[1] ESO Science Archive: http://archive.eso.org
[2] ESO contributed processed data: http://eso.org/rm/publicAccess#/dataReleases
[3] ESO pipeline-processed data: https://www.eso.org/sci/observing/phase3/data_streams.html
[4] Report of the ESO Working Group on Science Data Management (STC-580): https://www.eso.org/public/about-eso/committees/stc/stc-88th/public/STC_580_Data_management_working_group_report_88th_STC_Meeting.pdf
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[19] STILTS: http://www.star.bris.ac.uk/~mbt/stilts
[20] The ESOtap service: http://archive.eso.org/tap_obs
[21] The IVOA ObsCore data model (Louys et al., 2017): http://www.ivoa.net/documents/ObsCore
[22] Ambient conditions for Paranal: http://www.eso.org/asm/ui/publicLog?name=Paranal)
[23] Ambient conditions for La Silla: http://www.eso.org/asm/ui/publicLog?name=LaSilla
[24] Ambient conditions for APEX: http://www.apex-telescope.org/weather
[25] ESOtap server to catalogue data: http://archive.eso.org/tap_cat
[26] Programmatic and tool access demonstration page: http://archive.eso.org/programmatic
[27] IVOA DataLink v1.0 (Dowler et al., 2015): http://www.ivoa.net/documents/DataLink/index.html
[28] VO SSAP (Tody et al., 2012): http://www.ivoa.net/documents/SSA/20120210/REC-SSA-1.1-20120210.htm
[29] ESO Archive Community Forum: https://esocommunity.userecho.com
[30] IVOA standards: http://www.ivoa.net/documents/UWS/20140527/WD-UWS-1.1-20140527.html
[31] DALI: http://www.ivoa.net/documents/DALI/
[32] taplib: https://github.com/gmantele/taplib
[33] ESO implementation of tablib (G.Mantelet): https://github.com/vforchi/taplib
[34] ESO implementation of SSA on github: https://github.com/vforchi/SSAPServer

ESO/Juan Carlos Muñoz

The final image taken by VIMOS before it was decommissioned on 24 March 2018 was of the interacting galaxies NGC 5426 and NGC 5427, which form Arp 271.

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HAWK-I/GRAAL Science Verification

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Science Verification observations with the High Acuity Wide field *K*-band Imager (HAWK-I) instrument enhanced by the ground-layer adaptive optics module (GRAAL) were obtained during 4.5 nights from 2 to 6 January 2018. Fourteen projects were selected from a total of 19 submitted proposals. The total time scheduled for these 14 projects was 35.5 hours, which represents a slight oversubscription for the four allocated summer nights. The seven top-ranked projects were completed, three more programmes received some data, one was observed outside the requested constraints, and three projects were not started. The Science Verification nights were affected by various technical problems, mostly unrelated to GRAAL, which resulted in a total loss of 10 hours. Half a night was allocated on 6 January to compensate for some of the lost time. The atmospheric conditions were rather variable with occasionally excellent natural seeing (0.3 arcseconds). The ground layer turbulence fraction varied from 40% to 85% during these nights. The best performance in terms of improved image quality was observed when the ground layer fraction was above 70%, as expected for the system. The image quality in the *K* filter ranged between 0.2 arcseconds (in excellent conditions) to about 0.5 arcseconds (with mediocre seeing, > 0.8 arcseconds), and a small fraction of ground-layer turbulence. The delivered image quality was very stable, but in some cases an asymmetric point spread function was observed.

Proposal solicitation and submission

The call for HAWK-I/GRAAL Science Verification proposals and the corresponding web page were published on 2 October 2017[1]. The call was announced through the ESO Science Newsletter on 17 October 2017[2] with a deadline for proposal submission of 31 October 2017. Nineteen proposals were received by the deadline and evaluated by the Science Verification team over the following 2.5 weeks. A total allocation of 35.5 hours was chosen, a slight oversubscription compared to the available observing time (30 hours in total over four summer nights). This resulted in 14 projects being selected for scheduling. All Principal Investigators (PIs) were informed of the outcome of this selection process on 27 November, and the successful applicants were given a deadline for submission of the Phase 2 material of 14 December 2017. All PIs complied with this deadline and the submitted material was verified by the User Support Department before 22 December, so the HAWK-I/GRAAL Science Verification queue was ready by 31 December.

The scheduled projects covered a range of topics, including: the characterisation of a Solar System binary object — the dwarf planet Eris and its moon Dysnomia; observations of the mass function and dynamics of young clusters; pairs of stellar clusters and their origins; and a massive embedded cluster. Star formation projects included an investigation into the infrared excess emission of pre-main-sequence stars in the Large Magellanic Cloud (LMC) and observations of molecular hydrogen in a Herbig Haro object. Extragalactic topics included a potentially binary active galactic nucleus in a merging galaxy system, and multi-epoch observations of luminous infrared galaxies to search for core-collapse supernovae.

Observations

All observations were made without tip-tilt stars and using only the four laser beacons provided by the Adaptive Optics Facility (AOF). Various technical problems led to a loss of several hours during the Science Verification nights. At the same time some very good seeing conditions were encountered (down to 0.3 arcseconds). The image quality throughout was quite good (0.5 arcseconds), and nearly independent of the outside seeing with occasionally spectacular image quality in the fast photometry mode (0.2 arcseconds in *K*). In rare cases, an elongation of the images was observed, which was probably not related to the adaptive optics, as it has also been observed with other instruments on UT4. The only noticeable instrument issue during the run was a systematic instrument configuration tool error, revealed for non-zero position angles and corrected during the run.

The observations essentially followed the priority given by the ranking of the proposals. The seven top-ranked projects were completed fully within the requested constraints. Some data were obtained for three programmes, and for one project, the data did not comply within the requested constraints. The lowest-ranked three projects could not be started.

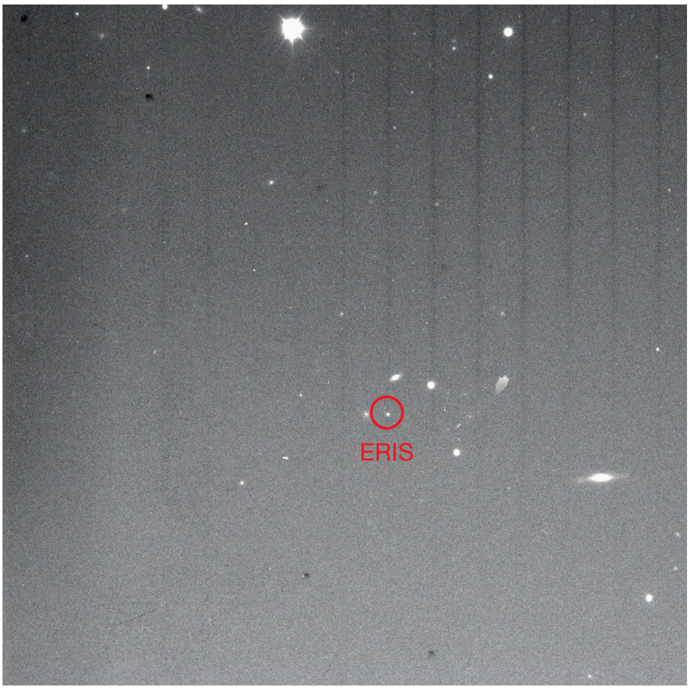
Archive and data processing

All raw and pipeline-reduced data are publicly available through the ESO science archive. The ESO data quality control group reduced all Science Verification data and the resulting products are available from the ESO Phase 3 data product form[3]. A new version of the HAWK-I/GRAAL data reduction pipeline has been released. The HAWK-I/GRAAL Science Verification web page also contains direct links to the Science Verification data in the archive[1].

Some early science results

Solar System objects: Eris and Dysnomia

Trans-Neptunian objects (TNOs) are icy/rocky bodies located beyond the orbit of Neptune, which are believed to be remnants of the building blocks from which planets formed. The dwarf planet (136199) Eris is one of the largest TNOs known in the Solar System, with a size similar to that of Pluto. During the HAWK-I/GRAAL Science Verification, high-precision photometric observations of Eris were obtained at near-infrared wavelengths. The aim of the observations was to characterise the surface heterogeneity



Cyrielle Opitom, Akhil Gunessee, Pascale Hibon

Figure 1. One of several images of Eris in one HAWK-I quadrant with a 3.6 × 3.6 arcminute field of view.

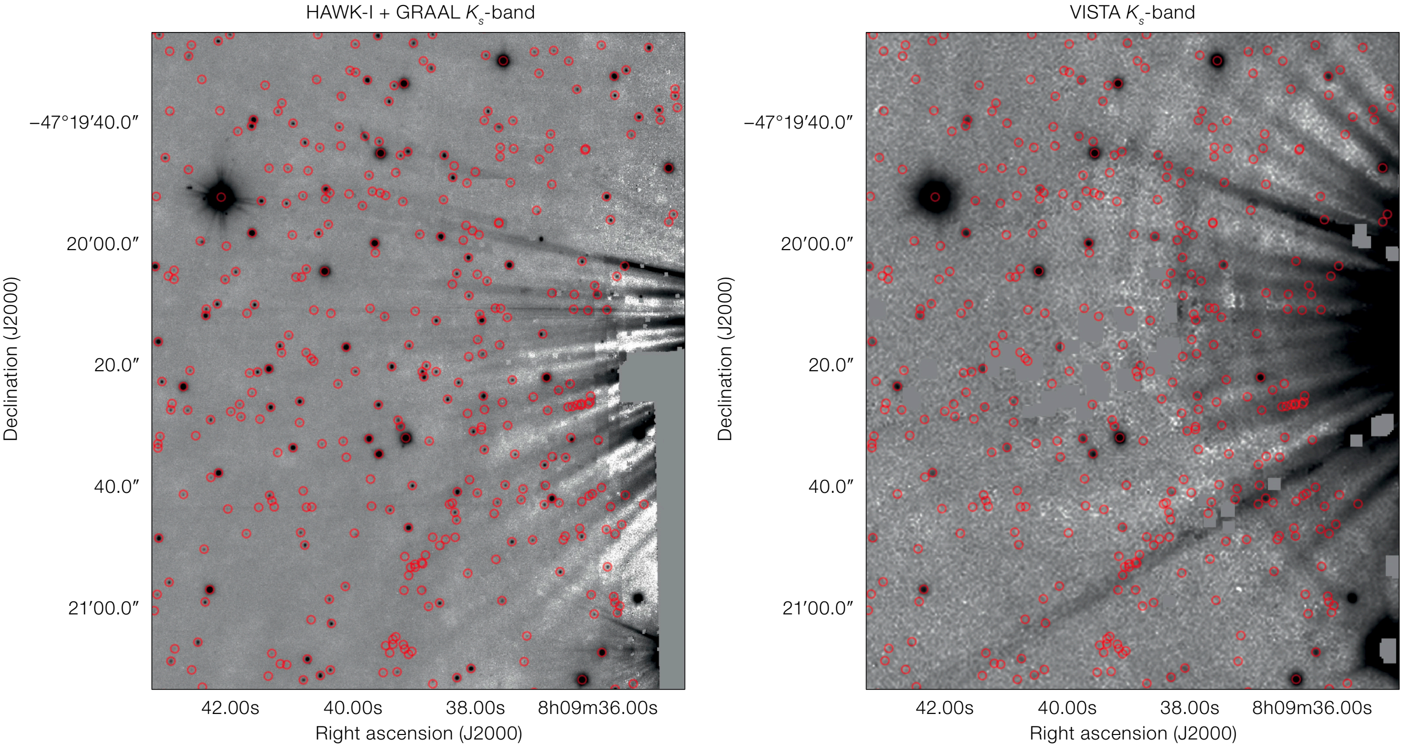
of this large TNO and detect photometric variations due to its rotation. Thanks to the performance of the GRAAL AO module (Figure 1), the team should be able to resolve Eris and its moon Dysnomia, whose separation varies between 0.3 and 0.5 arcseconds. A total of 18 high-quality images were obtained, spread over three consecutive nights. If photometric variations are detected in these observations, it will provide a way to definitively determine the rotation period of the dwarf planet Eris.

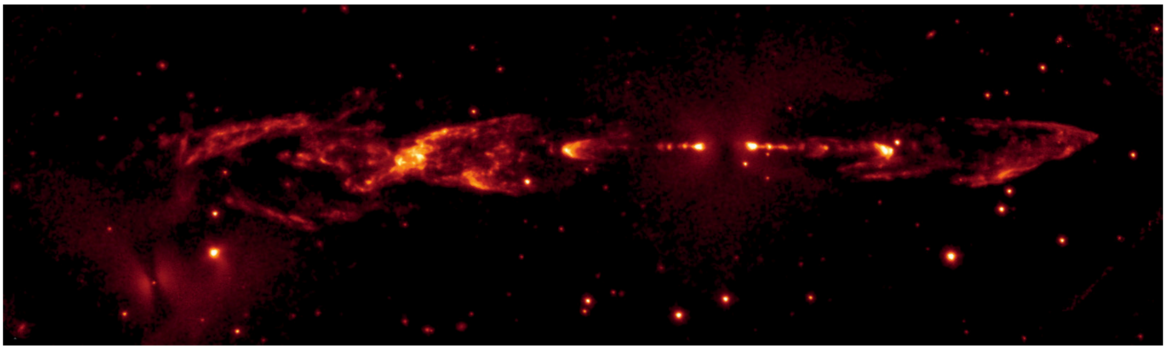
Probing the cores of nearby stellar clusters

The mass function and the dynamics of young clusters are among the most important observational constraints to the study of star formation. The presence of extremely bright, massive stars has prevented the analysis of environments in the cores of stellar associations. The γ Velorum cluster, which has an age of ~ 7 Myr and is at a distance of 350 pc, was targeted with HAWK-I/GRAAL specifically to observe the region around the naked-eye star γ Velorum (V = 1.8 mag). The star itself was carefully positioned outside the HAWK-I field of view and observations were obtained in the fast-photometry mode (integration time ~ 3.3 seconds, see Figure 2). This resulted in 2000 individual frames in K_s and 1040 frames in Y. A few frames with elongated images were discarded in the analysis. These data will ultimately provide a colour-magnitude diagram that will probe the stars down to about 5 Jupiter masses in the core of the cluster.

Figure 2. A comparison of HAWK-I/GRAAL images with archival VISTA observations around the star γ Velorum. The circles mark the sources detected in the HAWK-I frames.

Hervé Bouy





Christian Schneider

Figure 3. HH 212 in the H_2 filter at 2.12 µm with HAWK-I/GRAAL. The image shown here is 5 by 1.5 arcminutes.

Stellar outflows from young stars

Herbig-Haro objects are massive outflows driven by stellar systems in the making. They are large objects on the sky, extending over several arcminutes (~ 1 parsec), and appear mostly diffuse, although they also contain point-like substructures, which evolve on timescales of years. In fact, time evolution is key to understanding the physics of outflows, and in particular the link to their driving source: the planet-forming young stellar disc. Efficient mapping of Herbig-Haro objects requires wide-field, high-spatial-resolution data; this is exactly what HAWK-I provides in the near-infrared, where extinction effects are mitigated. Molecular hydrogen emission at 2.12 µm was observed in the Herbig-Haro object HH 212 using HAWK-I in 2007. The driving source of HH 212 is a low-mass protostar located in the Orion star-forming region at a distance of about 400 pc. The new HAWK-I/GRAAL Science Verification image of HH 212 shows all the characteristics of Herbig-Haro objects: well developed bow shocks, where the outflowing gas interacts with the ambient medium; jet-like features closer to the source, tracing the largely undisturbed flow originating in the star-disc system; and structure at essentially all scales. The new data (Figure 3) compared with the archival HAWK-I image will enable proper motions to be measured with high accuracy, i.e., down to 20 km s^{-1}, over the entire length of HH 212 — a fraction of the typical flow velocity of 300 km s^{-1}. A detailed comparison between the dynamics of the blue- and red-shifted lobes is especially interesting because, although HH 212 appears symmetrical, its lobes show substantially different space velocities, something that is challenging to explain with current jet launching models.

Young star cluster RCW38

RCW 38 is the youngest (< 1 Myr) of the Milky Way's 13 super star clusters (Fukui et al., 2016), and the densest stellar system within 4 kpc of the Sun (Kuhn et al., 2015). The cluster contains hundreds of protostars, pre-main sequence stars, and OB-star candidates (Winston et al., 2011), along with a substantial substellar candidate population revealed in the cluster core (Muzic et al., 2017). With HAWK-I/GRAAL data (see the cover image), one can directly study several key aspects of star formation: massive star birth; low-mass star and brown dwarf formation in a dense environment and under the influence of photoionisation fronts from massive stars; the initial mass function (IMF) on an unprecedented sample spanning three orders of magnitudes in mass; and mass segregation in young clusters.

Star-forming complex in the LMC

Pre-main-sequence candidate stars in the LMC often show near-infrared excesses compared to theoretical model predictions. This was discovered using VISTA images from the VISTA Magellanic Cloud survey (VMC; Cioni et al., 2011). However, the VISTA images are affected by crowding and photometric uncertainties, which could also mimic this excess. The HAWK-I/GRAAL Science Verification observations targeted the central area of the star-forming complex N44 to obtain a colour-magnitude diagram to well below 1 solar mass. The increased angular resolution has resolved the crowding problem — almost 3 times as many stars were detected in the densest young star cluster areas (Figure 4) — and also helped with independent photometry. If the near-infrared excess persists in these HAWK-I/GRAAL data as well, then it may be that the low metallicity in the LMC is responsible for significant changes in the early evolution of stars in such an environment.

Stellar cluster pairs in the LMC

The LMC possibly hosts the largest number of candidate stellar cluster pairs within the Local Group. These systems are extremely interesting as their study can provide a fresh look at the mechanisms of cluster formation and evolution. As part of a larger effort aimed at providing an independent characterisation of cluster pairs in the LMC (Dalessandro et al., 2018; Mucciarelli et al., 2012) this study exploited the wide field of view and the enhanced spatial resolution available with HAWK-I/GRAAL to observe the cluster pair NGC 2136 and NGC 2137 in the *J*- and *H*-bands. The high-quality colour-magnitude diagrams for the two clusters (Figure 5) will yield accurate cluster ages from the main-sequence turnoff luminosity, the structure of the systems from accurate star counts, and density profiles and the degree of mutual interaction. This information will, in turn, yield clues as to the origin and final fate of these stellar systems.

Supernovae in the cores of galaxies

Luminous infrared galaxies are highly star-forming and dust-obscured galaxies. While relatively rare in the local Universe, they start to dominate the total core-collapse supernova rates at $z \sim 1$. Two luminous infrared galaxies were observed during HAWK-I/GRAAL Science Verification. This resulted in the discovery of a new supernova, SN 2018ec (Kankare et al., 2018; Figure 6), in NGC 3256, which is only the second reported supernova in this luminous infrared galaxy, with an expected intrinsic core-collapse supernova rate of about one per year. Optical transient surveys did not discover this nearby supernova — at a distance of only 37 Mpc — owing to a combination of

Viktor Zivkov

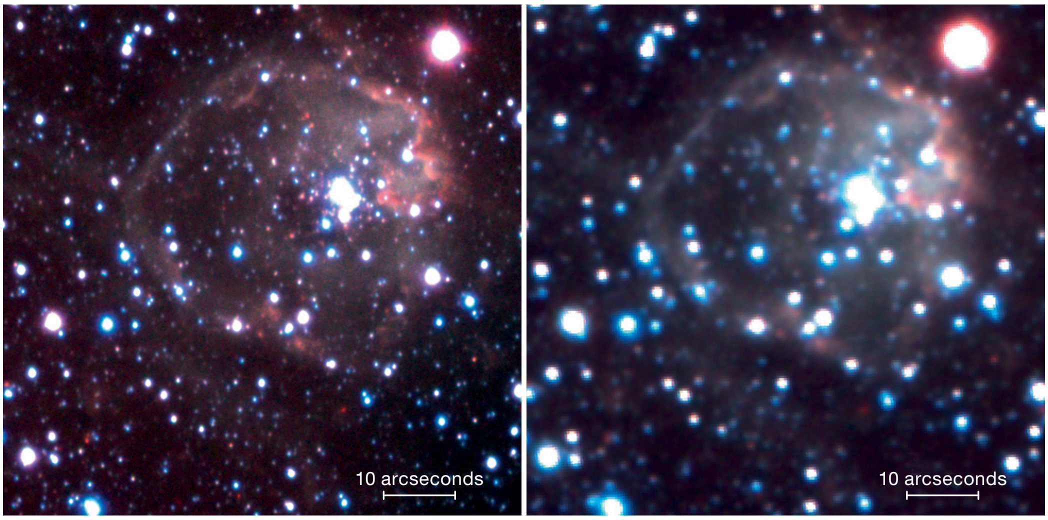


Figure 4. Comparison of HAWK-I/GRAAL (left) and VISTA (right) images of a region in the N44 star forming complex in the LMC.

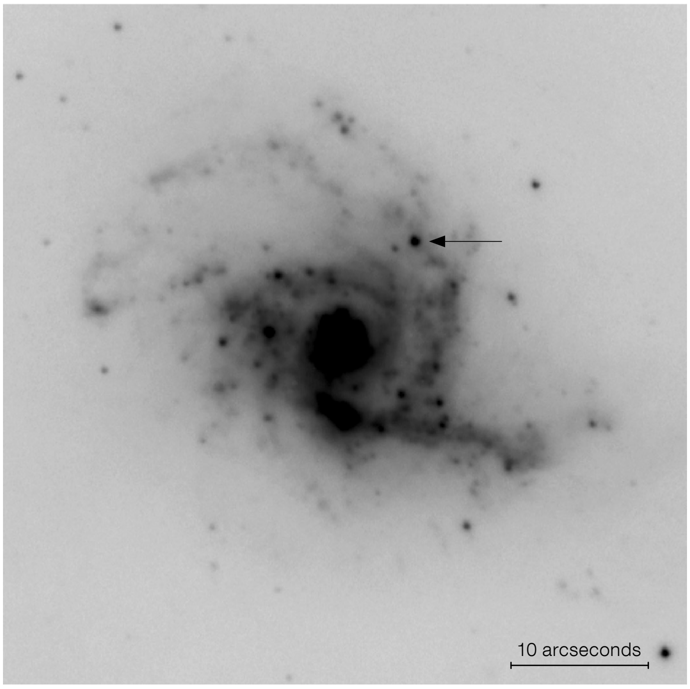
Emanuele Dalessandro

Figure 5. *J* and *H* colour-composite image of the binary cluster pair NGC 2136 and NGC 2137. The image size is 210 × 160 arcseconds.

the high extinction (A_V ~ 2 magnitudes) along the line of sight of the host galaxy and the high background. SN 2018ec was classified as a Type Ic supernova by the survey "extended-Public ESO Spectroscopic Survey for Transient Objects" (ePESSTO; Berton et al., 2018). The study of SN 2018ec will contribute to the long-term aim of deriving missing fractions for core-collapse supernovae from the local to the high-redshift Universe.

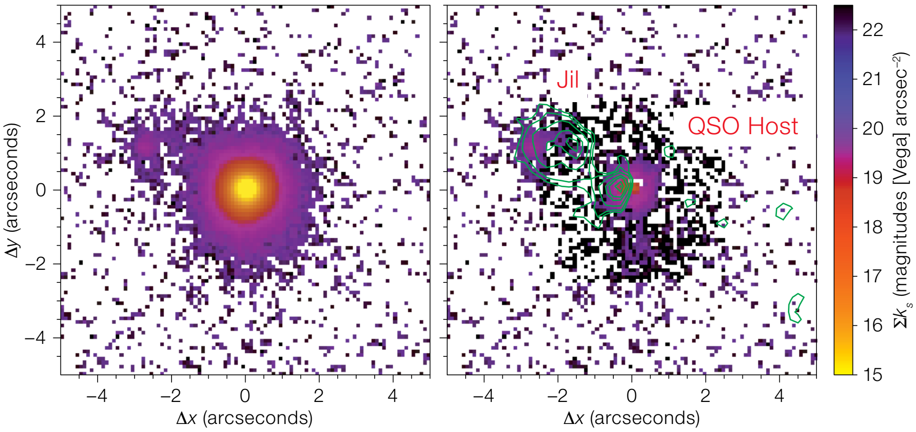
A dual active galactic nucleus?

Recent observations using the VLT instrument Multi Unit Spectroscopic Explorer (MUSE) uncovered a potential dual active galactic nucleus candidate at redshift $z = 3.3$ with a separation of only 20 kpc. The merging of supermassive black holes in galaxy mergers is expected in the hierarchical formation of galaxies. HAWK-I/GRAAL follow-up observations of this high-redshift dual active galactic nucleus system are crucial to characterising the coordinated assembly of the galaxies and the supermassive black holes. The goal of obtaining the K_s-band image (Figure 7) was to detect the host galaxy of the obscured active galactic nucleus. Indeed, the host galaxy was detected at the expected location (thanks to the exquisite image quality, of 0.4 arcseconds, and depth delivered by the adaptive optics system). After de-blending



Erkki Kankare

Figure 6. Discovery image of supernova SN 2018ec in NGC 3256 in a K_s image.



Bernd Husemann

Figure 7. Left panel: VLT/HAWK-I/GRAAL K_s-band image of the LBQS 0302-0019 dual AGN system. Right panel: Same as left, but the quasar light has been subtracted based on the PSF obtained froma nearby star. Significant extended emission is detected for the companion galaxy well above the surface brightness limit. The distribution of VLT/MUSE He II emission is shown by green contours. The emission peaks exactly at the location of the companion galaxy (dubbed “Jil”) with a slight preference towards the fainter asymmetric part of the continuum distribution.

the quasar plus companion galaxy system using the software package GALFIT3 (Peng et al., 2010), K_s-band magnitudes of 19.2 (Vega magnitudes) for the quasar host galaxy and 20.6 magnitudes for the companion galaxy were derived. At $z = 3.3$ the K_s-band corresponds nearly to the rest-frame velocity, and stellar masses of $\log(M_*/M_\odot) \sim 11.4$ and ~ 10.9 were derived for the quasar host and the companion, respectively (adopting a mass-to-light ratio of ~ 0.1 for a 200 Myr-old stellar population). The host galaxies are both very massive and probably trace one of the most massive dark matter halos at that epoch of the Universe (Husemann et al., 2018).

Acknowledgements

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We are grateful to Hervé Bouy, Christian Schneider, Kora Muzic, Viktor Zivkov, Emanuele Dalessandro, Erkki Kankare and Bernd Husemann, who kindly provided the images of the first HAWK-I/GRAAL Science Verification results.

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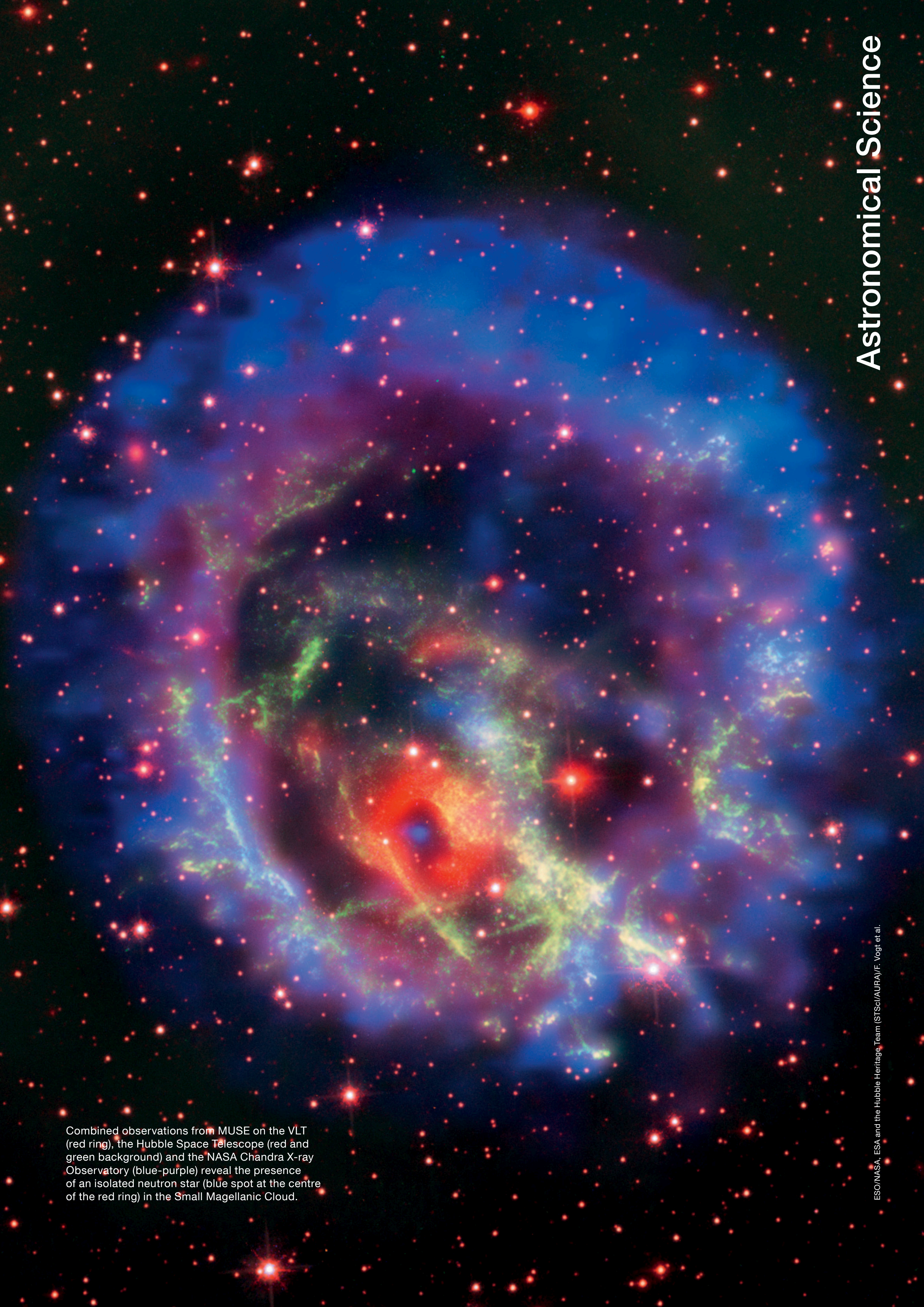
Links

[1] HAWK-I/GRAAL Science Verification web page: http://www.eso.org/sci/activities/vltsv/hawkigraalsv.html

[2] ESO Science Newsletter dated 17 October 2017: http://www.eso.org/sci/publications/newsletter/oct2017.html

[3] ESO Phase 3 data product query form for HAWK-I: http://archive.eso.org/wdb/wdb/adp/phase3_imaging/form?ins_id=HAWKI



Combined observations from MUSE on the VLT (red ring), the Hubble Space Telescope (red and green background) and the NASA Chandra X-ray Observatory (blue-purple) reveal the presence of an isolated neutron star (blue spot at the centre of the red ring) in the Small Magellanic Cloud.

ESO/NASA, ESA and the Hubble Heritage Team (STScI/AURA)/F. Vogt et al.

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ALMA Constrains the Stellar Initial Mass Function of Dusty Starburst Galaxies

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The stellar initial mass function (IMF) is fundamental to all measurements of cosmic star formation, which involves an extrapolation from rare, massive stars ($M_\star > 8\ M_\odot$) to the full stellar mass spectrum. Classical determinations of a galaxy's IMF are limited to ultraviolet, optical and near-infrared wavelengths, and these cannot be adopted for dust-obscured galaxies with intense, ongoing star formation, even in the local Universe. The unprecedented sensitivity of the Atacama Large Millimeter/submillimeter Array (ALMA) allows us to detect weak emission from ^{13}CO and C^{18}O isotopologues, which offer a sensitive, relatively dust-free, probe of the IMF. Globally low ^{13}CO/C^{18}O ratios for all our targets — dusty starburst galaxies at redshifts ~ 2–3 — alongside a detailed chemical evolution model imply that stars formed in extreme starburst environments are significantly biased towards massive stars compared to ordinary star-forming spiral galaxies. We have combined information from the coldest interstellar medium (at tens of Kelvins) with the physics of nucleosynthesis in hot stars (at tens of millions of Kelvins), to delineate the formation and evolution of galaxies. This opens up a new window to probe the stellar IMF of galaxies with ALMA and it challenges our understanding of fundamental parameters governing galaxy formation and evolution, such as star formation rates, and the timescales for gas depletion and dust formation.

The stellar initial mass function

First introduced by Edwin Salpeter (Salpeter, 1955), the stellar initial mass function is an empirical probability function which describes the relative numbers of stars that form in different mass ranges during a single star formation episode. The determination of the shape of the IMF — whether it is constant and universal or it depends on the physical conditions in the interstellar medium (ISM) out of which the stars form — is of the utmost importance for modern astrophysics, because of its fundamental role in all theories of star and galaxy formation.

Though neatly defined (more or less) from a theoretical point of view (Kroupa, 2001), the IMF is not easily derived from direct star counts (Bastian et al., 2010). Many challenges must be overcome in order to convert the observed stellar luminosities into stellar masses, where uncertainties in stellar distances, ages, metallicities, extinctions and the possibility of unresolved binary systems severely hamper our ability to measure the present-day mass function of a given stellar population. Furthermore, the effects of a complex star formation history and finite stellar lifetimes must be taken into account to recover the IMF from the present-day mass function. For example, the more massive a star, the less time it takes to evolve off the main sequence; at the same time, low-mass stars — with lifetimes comparable to the age of the Universe — continue to populate the present-day mass function. This readily introduces a bias against high-mass objects.

Deducing the shape of the IMF from its chemical imprint

Estimating the IMF directly is therefore anything but a trivial task. On top of this, direct observations of stellar light are not always possible.

The most massive and luminous galaxies that shine at high redshift — for instance, those producing stars at tremendous rates (for example, in excess of 1000 $M_\odot$ yr^{-1}, see Ivison et al., 1998) — have their ultraviolet and optical stellar light heavily obscured by dust (see Figure 1). However, according to theories and cosmological simulations, it is in exactly these systems where the most extreme IMF variations would arise. Are there any other sensible, indirect methods to probe the IMF in these important, dust-shrouded systems?

Luckily, carefully selected chemical abundances (see the next sections) can be measured at millimetre/submillimetre wavelengths — a regime relatively free from the pernicious effects of dust; these provide a fossil imprint of the chemical enrichment processes and an indirect constraint on the prevailing stellar IMF in those extreme environments. It is well known (for example, Tinsley, 1980) that stars in different mass ranges produce different elements in different proportions and on different timescales, with the initial chemical composition of the stars also playing a role. Indeed, in the last three decades, systemic variations of the IMF slope have been explored with the aid of increasingly refined galactic chemical-evolution models. These attempt to explain, for instance, the overabundance of magnesium with respect to iron in local elliptical galaxies, where magnesium is synthesised on short timescales by massive stars and iron is produced mostly on long timescales by type Ia supernovae with relatively low-mass progenitors, or the low metallicities measured in gas-rich, star-forming dwarf galaxies. However, differences in star formation timescales and/or galactic outflows have sometimes shown to act in a similar way, making it very difficult to prefer a variable IMF over other possibilities (Matteucci, 1994).

Carbon, nitrogen and oxygen production in stars, and mixing in the ISM

The seven stable isotopes of carbon, nitrogen and oxygen (the CNO elements) are produced solely by nucleosynthesis in stars. On galactic scales, ^{13}C and ^{18}O are released predominately by low- and intermediate-mass stars ($M_\star < 8\ M_\odot$) and massive stars ($M_\star > 8\ M_\odot$), respectively (Kobayashi et al., 2011). This is due to the differing energy barriers in nuclear

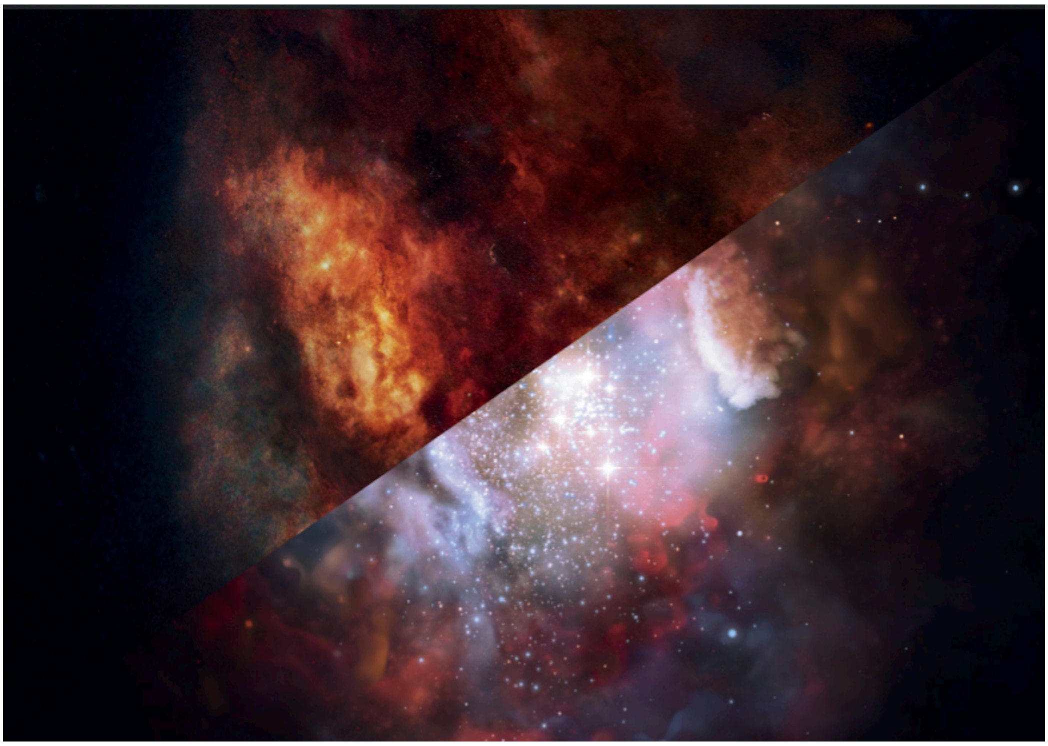

Figure 1. Artist's impressions of a dusty starburst galaxy. The star formation rate is supposedly a few hundred $M_\odot$ yr^{-1}. The dusty curtain obscures the optical and ultraviolet (and, sometimes even the near-infrared) light from stars and only emission at much longer wavelengths, i.e., from submillimetre/millimetre to centimetre can escape. Classical, direct measurements of the present-day mass function are simply not possible for such galaxies.

reactions and the mass-dependent evolution of stars.

^{13}C is mostly synthesised as a secondary element, i.e., its production needs the pre-existing seed of the primary element, ^{12}C, to be present at a star's birth. However, ^{13}C also has a primary production channel, if synthesised directly from ^{12}C produced through helium burning in the star itself. This may happen at the base of the convective envelopes of asymptotic giant branch (AGB) stars going through periodic episodes of dredge-up (Renzini & Voli, 1981), or in low-metallicity, fast-rotating, massive stars, in which rotation triggers the production of primary ^{13}C by allowing the diffusion of ^{12}C produced in He-burning zones into zones burning hydrogen (Chiappini et al., 2008).

Massive stars dominate the production of ^{18}O (Timmes et al., 1995), which is mostly synthesised as a secondary element in the early stages of helium burning, starting from any pre-existing ^{16}O. Therefore ^{18}O production is strongly dependent on the initial stellar metallicity.

These isotopes are then ejected into the ISM via stellar winds, where they form molecules in the same way as their major isotopes. Measurements of ^{13}CO and C^{18}O — isotopologues of carbon monoxide, ^{12}C^{16}O or CO — in the ISM can thus be used to trace the relative ^{13}C and ^{18}O abundances produced by successive generations of stars.

In theoretical work by Romano et al. (2017), we reassessed the relative roles of stars in different mass ranges in the production of the rare CNO isotopes, ^{13}C, ^{15}N, ^{17}O and ^{18}O, along with the more abundant ^{12}C, ^{14}N and ^{16}O. We used a proprietary galactic chemical evolution code for the Milky Way and stellar yields from the literature for massive stars, AGB stars and novae to show that the available isotopic data for the local ISM, protosolar nebula, metal-poor stars and abundance gradients across the Galactic disc can be reproduced satisfactorily with a suitable choice of yields. Moreover, we showed that our models could be extended to constrain the stellar IMF of star-forming galaxies across cosmic time. Among the remaining uncertainties, an unknown star formation history is particularly tricky to deal with. However, if galaxies are caught during the earliest stages of their evolution, the uncertainties are significantly reduced.

ALMA observations of ^{13}CO and C^{18}O towards dusty starbursts

Starburst galaxies in the local Universe most likely had prior episodes of cosmological evolution, so the elementary abundances in their ISM could be affected by a complex star formation history may not strictly be related to the current episode of star formation. We selected a sample of dusty starburst galaxies at $z \sim 2–3$, with less than 3 Gyr of cosmic time available for prior episodes of evolution. So they are expected to have relatively clean and simple star formation histories. Owing to the weakness of the isotopologue lines (^{13}CO and C^{18}O), we selected the four strongest CO emitters in the literature, which are all gravitationally lensed systems with their signals amplified by factors of ~ 3–10.

We performed simultaneous observations of ^{13}CO and C^{18}O emission lines, using ALMA in its relatively compact array configurations, in the spring of 2015 (Zhang et al., 2018). Between 10 and 30 minutes were spent on each target per observation. We manually calibrated all data using the Common Astronomy Software Applications (CASA) package[1] (v. 4.7.1) following standard procedures. The final angular resolution spanned 1.6 to 3.7 arcseconds, corresponding to spatial resolutions of ~ 14–30 kpc at $z \sim 2$. We optimised for sensitivity, both in the observations and in the data reduction, so the final images have limited angular resolution — most targets are unresolved or only marginally resolved.

Most targeted lines are detected robustly with signal-to-noise (S/N) > 5. Only two targeted lines are marginally detected at ~ 4-σ level; $J = 3 \rightarrow 2$ from SDP.17b (HATLAS J090302.9–014127) and $J = 5 \rightarrow 4$ from SPT 0103–45 (SPT-S J010312–4538.8). However, the high-J transitions show consistent results at higher S/N, so we can be confident about the observed line ratios. See Figure 2 for an example of our ALMA detections of ^{13}CO and C^{18}O, $J = 3 \rightarrow 2$.

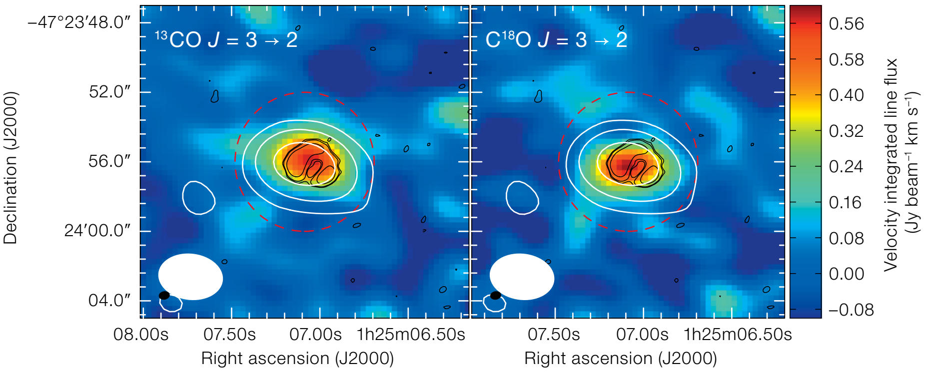

Figure 2. Velocity-integrated flux map (zero moment) of ^{13}CO and C^{18}O for the $J = 3 \rightarrow 2$ transition in SPT 0125–47. White contours show the low-resolution 94-GHz continuum, tracing the rest-frame cold dust emission. Black contours show the high-resolution 336-GHz continuum image, obtained from the ALMA archive, presenting the Einstein ring structure produced by the gravitational lensing effect.

Literature data on ^{13}CO and C^{18}O in various galaxies

We compiled a collection of line flux ratios from the literature, $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ at the same J transitions, in various types of gas-rich galaxies. Figure 3 shows the $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ ratio as a function of infrared luminosity, L_{IR} (i.e., the apparent star formation rate traced by massive stars).

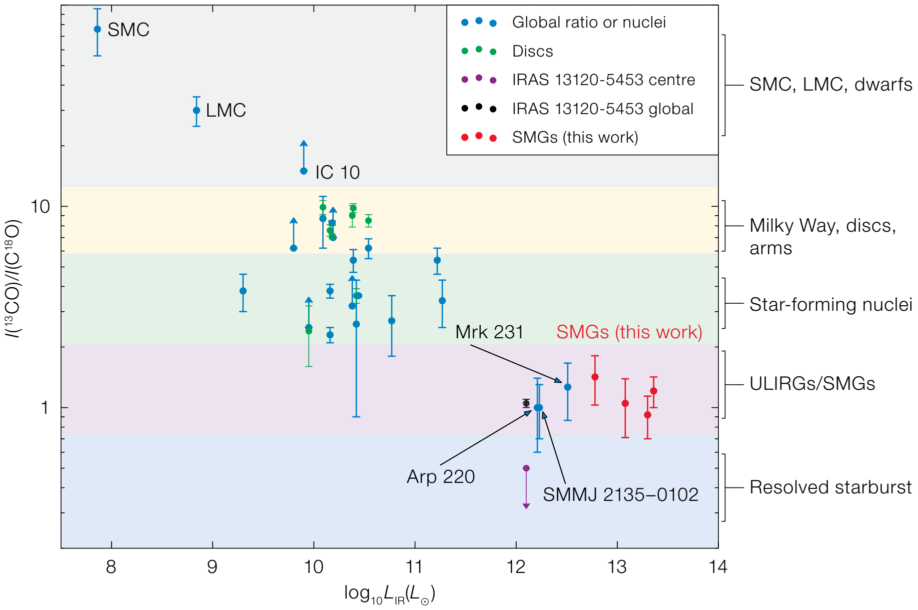

Figure 3. $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ as a function of intrinsic infrared luminosity (rest-frame 8–1000 μm, L_{IR}). Our lensed starburst sample is plotted with red symbols. The $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ measurements of nearby star-forming galaxies, galactic nuclei (Jiménez-Donaire et al., 2017), local Ultraluminous infrared galaxies (ULIRGS; Henkel et al., 2014), a lensed submillimetre galaxy (SMG), SMM J2135–0102 (Danielson et al., 2013), gas-rich dwarf galaxies, the Magellanic Clouds (SMC and LMC) and IC 10, are presented for comparison.

Discs of nearby normal spiral galaxies have $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ line ratios of ~ 7–10, similar to that of the Milky Way's disc (Jiménez-Donaire et al., 2017). Galaxies with extremely high star-forming activity (≥ 100–500 × Milky Way) all have much lower ratios, close to unity (Henkel et al., 2014). The lowest $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ ratio, an upper limit of 0.5, is found in a starburst knot — the central 500-parsec region of the nearby ultra-luminous infrared galaxy IRAS 13120–5453 (Sliwa et al., 2017). Gas-rich dwarf galaxies, such as the Magellanic Clouds and IC 10, show the highest ratios of $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$, greater than 30. $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ shows a clear decreasing trend with L_{IR}, or the apparent star formation rate traced by massive stars.

Both the ^{13}CO and C^{18}O lines are excited predominantly by collisions with H_2 molecules, so they share identical excitation conditions. These lines are optically thin, given their low abundances. Their abundances are not biased by differential astro-chemical effects and differential lensing effects for the bulk of the molecular gas in galaxies. So the line ratio of $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ can be used safely to trace the abundance ratio of ^{13}CO/^{18}O in the ISM.

Such a systematic variation of isotopologue abundance ratios over galaxy-sized molecular hydrogen reservoirs indicates a change of the stellar IMF from the canonical one found in normal star-forming systems like the Milky Way. To verify this, the degeneracy with star formation history needs to be taken into account, because the lifetimes of stars can also bias the final abundances in the ISM.

Galactic chemical evolution

How much variation does the star formation history induce in the ^{13}C/^{18}O ratio, compared to any changes due to variations of the IMF slope? To answer this

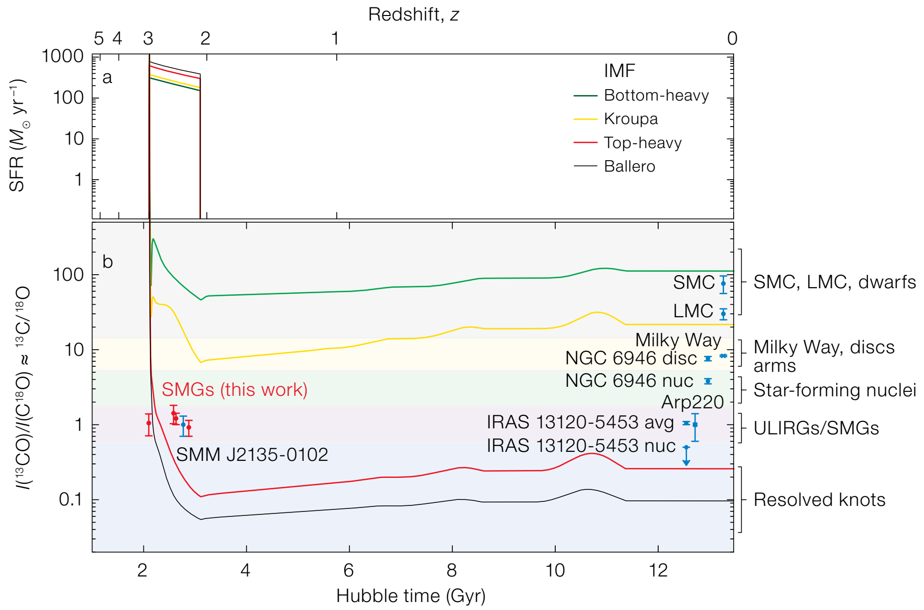

Figure 4. Evolutionary tracks of $^{13}C/^{18}O$ abundance ratio in the ISM, using various IMFs. Coloured lines correspond to different IMFs. a) Modelled starburst history, which started evolving 2 Gyr after the Big Bang, grew to a total stellar mass of 10^{11} $M_{\odot}$ and stopped forming stars 1 Gyr later. SFR is the star formation rate. b) Corresponding $^{13}CO/C^{18}O$ (as a proxy of $^{13}C/^{18}O$) abundance ratio as a function of redshift, following different IMFs. Our lensed starburst sample is plotted with red symbols. Blue dots show the $^{13}CO/C^{18}O$ ratios measured in a few representative local galaxies.

question, we adopt a galactic chemical evolution model that accurately includes the isotopic yields across the full range of stellar mass, taking into account the differential release of different elements into the ISM as a function of a star's lifetime, and the initial metallicity, as well as any prior galactic evolution. We have benchmarked the model against the rich isotopic datasets of the Milky Way and shown it can reproduce the Galactocentric gradients of isotopic abundance ratios, and all the relevant local disc data (Romano et al., 2017).

With such a well-calibrated model, we can safely build up an extreme case for the evolution of the $^{13}C/^{18}O$ abundance ratio for a pure starburst, as shown in Figure 4. To do that, we evolve a galaxy from $z \sim 3$ (2 Gyr after the Big Bang) for a span of 1 Gyr, with a high star formation rate, until it reaches a total stellar mass of 10^{11} $M_{\odot}$. Star formation is stopped completely after that, and the relic evolves passively to $z \sim 0$. This model was repeated with four different types of IMF, from bottom-heavy (biased towards low-mass stars) to top-heavy (biased towards massive stars), including the canonical Kroupa IMF that can reproduce average Galactic conditions (Kroupa, 2001).

With the Kroupa IMF, the evolved $^{13}C/^{18}O$ ratio reaches the range observed in the discs of the Milky Way and nearby normal spiral galaxies. However, only a top-heavy IMF can reproduce the $I(^{13}CO)/I(C^{18}O)$ observed in starburst galaxies, near and far. The extremely low $I(^{13}CO)/I(C^{18}O)$ ratio measured in the centre of IRAS 13120–5453 can be explained with the top-heavy and the Ballero IMF (Ballero et al., 2007), which could reproduce the chemical abundances of stars in the Galactic bulge.

Outlook and implication

Our results — finding a top-heavy IMF in dusty starburst systems across cosmic time, where classical IMF measurement methods cannot be applied — are consistent with the results from other, less dusty, less extreme starburst systems, such as ultra-compact dwarf galaxies, progenitors of early-type galaxies, and compact starbursting stellar associations in the Large Magellanic Cloud.

The systematic variation of the IMF in different galaxy types has an obvious dependency on their star formation properties. The IMF can no longer be assumed to be universal, with a constant canonical form, as commonly applied in most cosmological simulations. Moreover, all measurements of cosmic star formation rate and stellar mass, and their derivatives, must be re-assessed urgently. For example, the star formation rates in starburst galaxies are derived from classical tracers, which extrapolate observables from massive stars using an assumed IMF. These need to decrease by a factor of at least a few, and the gas-depletion times must then increase by the same factor. As a result, most fundamental parameters in the field of galaxy formation and evolution must be re-addressed, exploiting advances in stellar physics.

Acknowledgements

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Links

[1] CASA software: https://casa.nrao.edu/index.shtml

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MIKiS: the ESO-VLT Multi-Instrument Kinematic Survey of Galactic Globular Clusters

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Globular clusters are collisional systems, where stars of different masses orbit and mutually interact. They are the best "natural laboratories" in the Universe for studying multi-body dynamics and their (reciprocal) effects on stellar evolution. Although these objects have been studied since the very beginning of modern astrophysics, little is known observationally about their internal kinematics, thus preventing a complete understanding of their dynamical state, and of their formation and evolutionary history. We present the first results from the Very Large Telescope (VLT) Multi-Instrument Kinematic Survey of Galactic globular clusters (MIKiS), which is specifically designed to provide line-of-sight velocities of hundreds of individual stars over the entire radial extension of a selected sample of clusters. The survey allows the first kinematical exploration of the innermost regions of high-density globular clusters. When combined with proper motion measurements, it will provide the full 3D view in velocity-space for each system. Long-running open issues, such as the accurate shapes of the velocity dispersion profiles, the existence of systemic rotation and orbital anisotropy (and thus the level of relaxation), and the controversial presence of intermediate-mass black holes in star clusters can finally be addressed, impacting our understanding of the formation and evolutionary processes of globular clusters and their interactions with the Galactic tidal field.

Galactic Globular Clusters are gas-free stellar systems, made up of a few times 10^5 stars of different masses (typically from ~ 0.1 to 0.8 $M_{\odot}$). They are the most populous, and the oldest stellar systems in which stars can be individually observed. Moreover they are the sole cosmic structures that, within the timescale of the age of the Universe, undergo nearly all of the physical processes known in stellar dynamics. Galactic globular clusters are true touchstones for astrophysics. The study of their stellar populations is crucial to validating predictions from stellar evolution theory, and they are invaluable laboratories for multi-body dynamics. Surprisingly, while remarkable progress has been made in the study of Galactic globular cluster stellar populations (see Carretta et al., 2009 and Piotto et al., 2015), the kinematical characterisation of these systems is just in its infancy and the modelling often relies on a set of over-simplified assumptions.

In general, globular clusters are assumed to be quasi-relaxed, non-rotating stellar systems, characterised by spherical symmetry and orbital isotropy, with structural and kinematical properties (surface brightness and velocity dispersion profiles) that are well captured by a truncated Maxwellian distribution function (for example, King, 1966). However, growing observational evidence demonstrates that although this scenario is correct to a first approximation, it is largely oversimplified. Indeed, there is accumulating evidence of significant deviations from sphericity (Chen & Chen, 2010), and from a King density profile, a profile used to fit the observed distribution of stars within a globular cluster as a function of their distance from the centre (see Carballo-Bello et al., 2012; Lane et al., 2010). Signatures of systemic rotation and pressure anisotropy have been detected in several clusters (for example, Watkins et al., 2015; Kamann et al., 2018; and references therein).

Thus, despite its importance, our empirical knowledge of globular cluster internal kinematics from the very centre (where the most interesting dynamical phenomena occur) to the tidal radius (where the effects of the Galactic tidal field are visible) is still critically inadequate. In particular, a detailed knowledge of the velocity dispersion profile and the (possible) rotation curve is still missing in the majority of the cases. This is essentially due to observational difficulties.

In principle, velocity dispersion and rotation can be obtained from different approaches. In practice, however, the standard methodology commonly used in extra-galactic astronomy (i.e., measuring radial velocities from Doppler shifts and velocity dispersions from the line broadening of integrated-light spectra) can suffer from severe shot-noise bias in Milky Way globular clusters, because the acquired spectrum can be dominated by the contribution of just a few bright stars (for example, Dubath et al., 1997). In the case of resolved stellar populations, a safer approach is to determine velocity dispersion and rotation from the velocities of individual stars. By combining the line-of-sight information (measured through resolved spectroscopy) with the two velocity components on the plane of sky (from internal proper motions), a full 3D view of the velocity space of the system can be obtained. This begins to be feasible in Galactic globular clusters.

Internal proper motions require high-precision photometry and astrometry on relatively long time baselines. These are finally achievable thanks to multi-epoch HST and Gaia observations. The former are providing the necessary information on the centres of Galactic globular clusters (even if the innermost regions of the densest systems might still be missed; for example, see Bellini et al., 2014 and Watkins et al., 2015 for recent results). In the meantime, Gaia is providing the complementary measures in the outskirts. The line-of-sight kinematical information over the entire radial extension of Galactic globular clusters is still largely missing, because it requires the collection of large samples of individual stellar spectra, both in highly crowded regions — the central density of the Milky Way globular clusters can reach up to 7×10^5 $L_{\odot}$ parsec^{-3} (see

Harris, 1996 and 2010) — and over large sky areas (from 20–40-arcminute diameter and even more). This is conceptually easy but operationally challenging and requires a lot of telescope time. To fill this gap in globular cluster studies and overcome these difficulties, we recently conducted a spectroscopic campaign based on a synergic use of three different VLT facilities.

The survey

The Multi-Instrument Kinematic Survey of Galactic globular clusters (hereafter the MIKiS survey; Ferraro et al., 2018) has been specifically designed to provide the velocity dispersion and rotation profiles of a representative sample of Milky Way globular clusters over their entire radial extension. With this aim, it takes advantage of the specific characteristics of three different instruments installed at the VLT, allowing multi-object spectroscopy with the appropriate angular resolution, depending on the radial region surveyed. The survey is based on two ESO Large Programmes (193.D-0232 using the *K*-band Multi-Object Spectrograph [KMOS] and the Fibre Large Array Multi Element Spectrograph [FLAMES], and 197.D-0750 using SINFONI; Principal Investigator Francesco Ferraro) and has been designed with the core scheme described below.

1. **Diffraction-limited integral-field spectroscopy with adaptive-optics-assisted SINFONI**
   These observations are used to resolve stars in the innermost few arcseconds of the highest-density clusters. We adopted the SINFONI *K*-band grating to achieve high Strehl ratios. To symmetrically sample the spatial distribution of stars (which is necessary to properly construct the rotation curve) we planned a mosaic of between 4 and 9 pointings in the 125-millarcsecond mode (125 × 250 milliarcseconds/pixel, 8 × 8 arcseconds field of view). In the densest clusters, an additional central pointing was also planned in the 50-milliarcsecond mode (50 × 100 milliarcseconds/pixel, 3 × 3 arcseconds field of view). With the selected setup (*K* grating, $R = 4000$), radial velocities can be properly measured from molecular CO bandheads in the coolest giants ($T_{\rm eff} < 5000$ K) and from some atomic lines in the warmer stars. Note that, in the MIKiS approach, integral-field spectroscopy is used in a non-conventional way; instead of using integrated-light spectra at various distances from the cluster centre, we extract the spectrum of each distinguishable individual star from the most exposed spatial pixel (spaxel) corresponding to the star centroid in the data cube. Typically several dozens of giants have been observed down to $K \sim 15$ in each cluster with the planned mosaics (see Figure 1).

2. **Seeing-limited observations with the multi-integral-field spectrograph KMOS**
   These observations have been performed for an optimal coverage of the intermediate radial range (a scale of tens of arcseconds). KMOS is a spectrograph equipped with 24 deployable integral-field units (IFUs) that can be allocated within a 7.2-arcminute diameter field of view. Each IFU covers a projected area on the sky of about 2.8 × 2.8 arcseconds, sampled by an array of 14 × 14 spaxels with an angular size of 0.2 arcseconds each. We have used the *YJ* grating covering the 1.00–1.35 μm spectral range at a resolution $R = 3400$. This instrument setup is especially effective at simultaneously measuring a number of reference telluric lines in the spectra of giant stars for an accurate calibration of the radial velocity, despite the relatively low spectral resolution. Typically, 7–8 pointings have been secured in each cluster. We selected red giant targets with $J < 14$, with no stars brighter than $J = 15$ within 1 arcsecond from their centre. In order to minimise the effects of possible residual contamination from nearby stars and/or from the unresolved stellar background, the 1D spectra were extracted manually by visually inspecting each IFU and selecting the brightest spaxel corresponding to each target star's centroid. Normally, one star was measured in each IFU though in a few cases two or more resolved stars were clearly distinguishable in a single KMOS IFU (see Figure 2), and their spectra were extracted.

3. **Wide-field multi-object spectroscopy with FLAMES.** This has been exploited to sample the external cluster regions, i.e., out to several arcminutes. We used FLAMES in the combined GIRAFFE-MEDUSA mode, which consists of 132

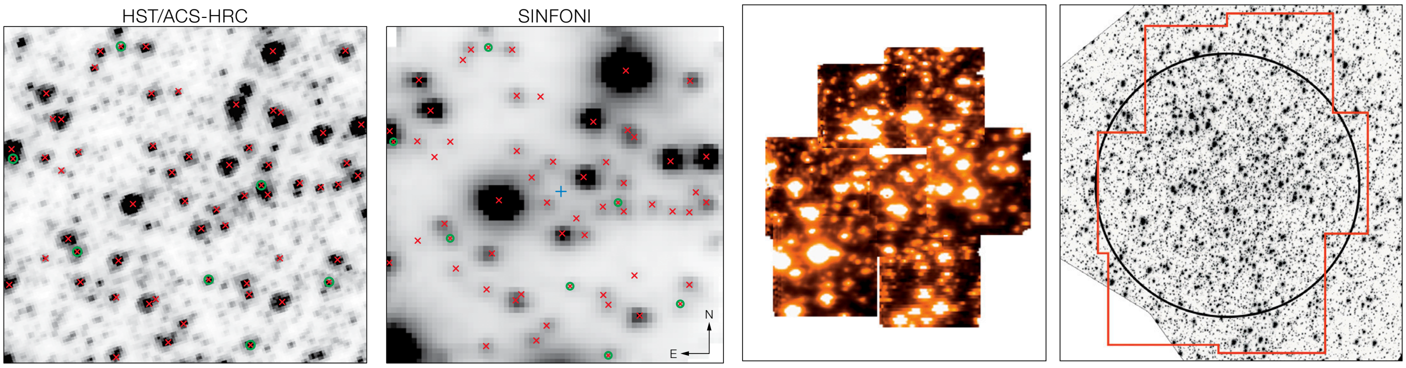

Figure 1. Left panels: Comparison between a reconstructed SINFONI image and an HST/ACS-HR C image of the innermost 3 × 3 arcseconds of NGC 6388. Each SINFONI spaxel provides a spectrum. The red crosses correspond to the stellar centroids identified from the HST image; 52 individual RVs have been measured within 1.5 arcseconds from the cluster centre. Right panels: The same in the case of NGC 2808, where 700 individual spectra of resolved stars were extracted within 10 arcseconds from the centre.

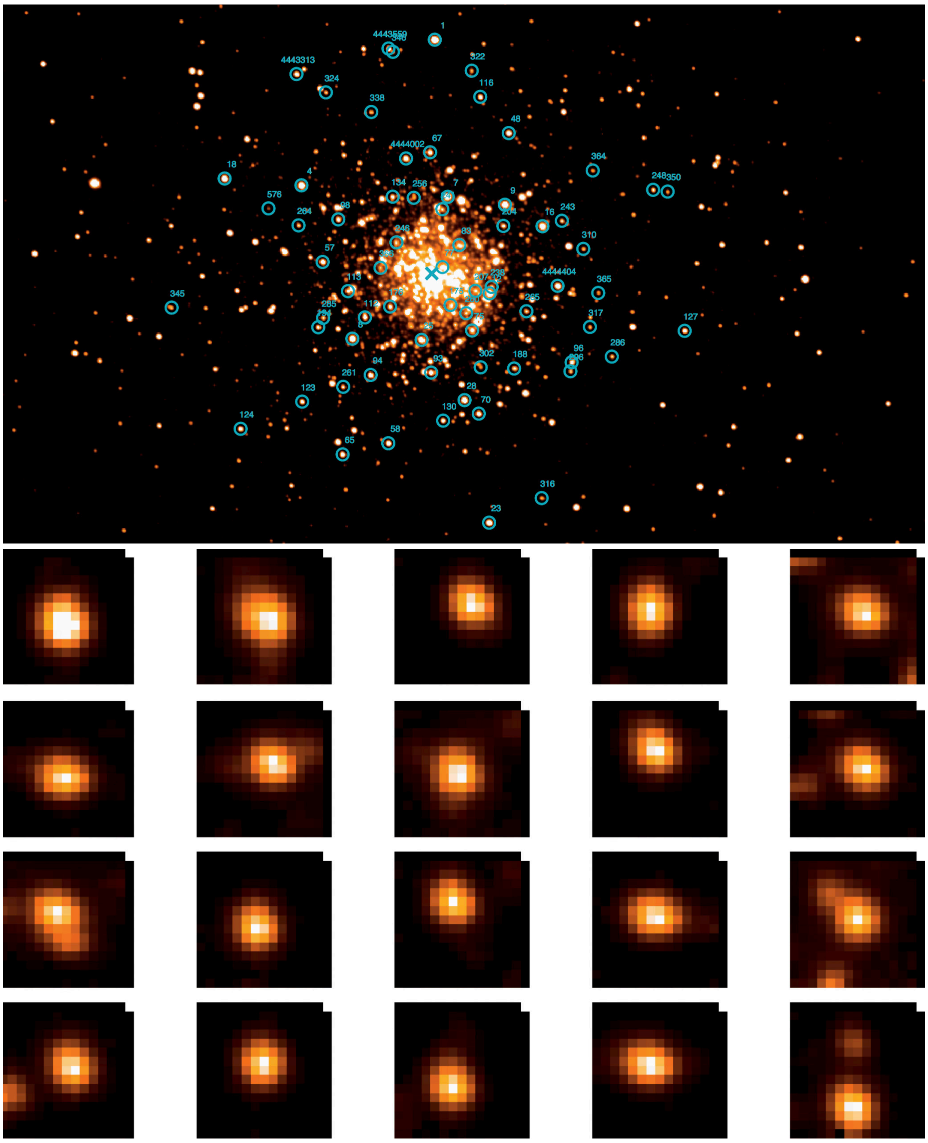

Figure 2. The map in the upper panel shows the location of the targets observed with KMOS in NGC 6388. Lower panel: reconstructed images for 20 IFUs in a typical pointing.

deployable fibres that can be allocated within a 25-arcminute diameter field of view. The adopted HR 21 grating setup, with a resolving power $R = 16\,200$ and spectral coverage from 8484 to 9001 Å, samples the prominent Ca II triplet lines, which are excellent features from which to measure radial velocities. The selected targets are essentially red giant branch stars brighter than $I = 18.5$. In order to avoid spurious contamination from other sources within the fibres, only isolated stars with no bright neighbours within 2 arcseconds from each target were selected. On average, 3–4 pointings were performed in each cluster.

This approach was first tested, as a proof of concept, on the Galactic globular clusters NGC 6388 (Lanzoni et al., 2013, Lapenna et al., 2015) and NGC 2808 (see Figures 1 and 2). Then, for the MIKiS survey we selected 30 massive globular clusters across the entire Galaxy (Figure 3), sampling both the bulge/disc stellar populations close to the Galactic plane (at $z < 1.5$ kpc) and the halo ones (at $1.5 < z < 13$ kpc).

The targets properly map the parameter space most sensitive to the internal dynamical evolution of the cluster, covering a wide range of central densities and concentration parameters[a] ($2.5 < c < 0.5$), and sampling all the stages of dynamical evolution, including both pre- and post-core-collapse globular clusters (with a core relaxation time spanning almost 3 orders of magnitude). For a reliable determination of the line-of-sight velocity dispersion profile the selected globular clusters are also populous enough (i.e., more luminous than $M_V = -6.5$) to provide large samples of giant/sub-giant stars. To measure stars along a relevant portion

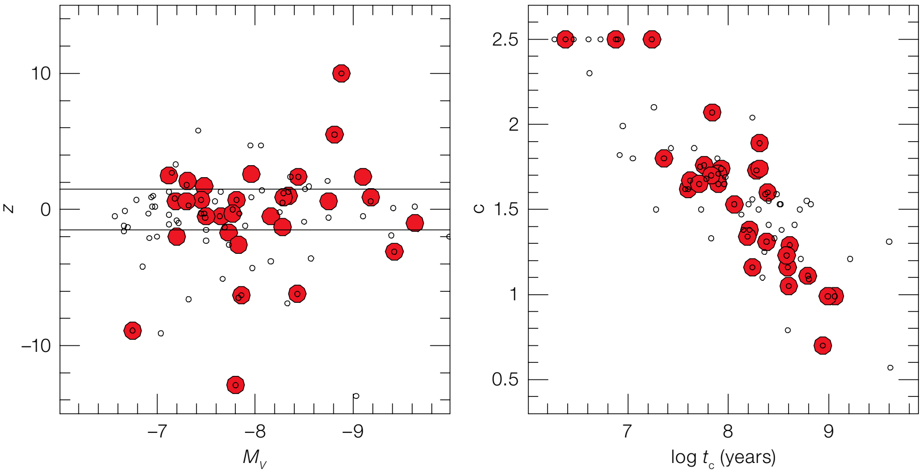

Figure 3. Distribution of the targets selected for the MIKiS survey (large circles) showing the height on the Galactic plane z *vs.* absolute integrated V-band magnitude M_V (left) and the King concentration parameter c *vs.* core relaxation time t_c (right). The total Galactic globular cluster population is also plotted for reference (small dots).

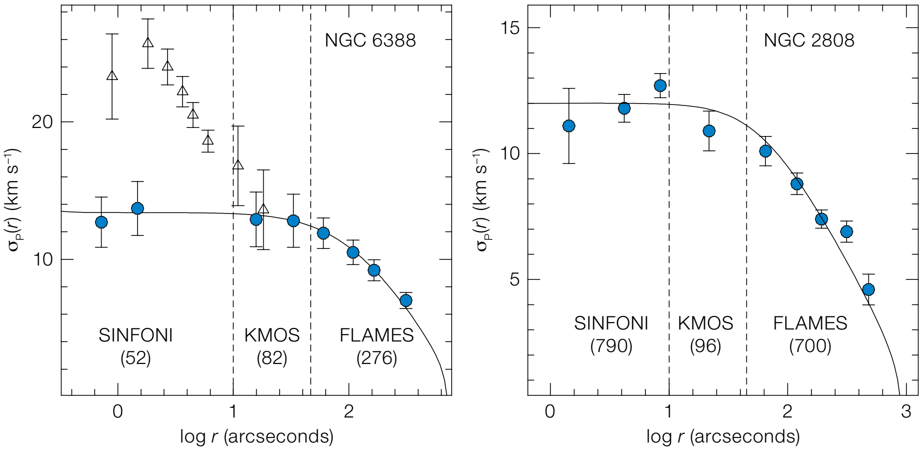

Figure 4. Velocity dispersion profiles of NGC 6388 and NGC 2808 obtained from the radial velocities of individual stars (blue circles) measured following our multi-instrument approach: SINFONI+KMOS+-FLAMES. The number of individual spectra measured with each instrument is labelled. The empty triangles in the left-hand panel show the velocity dispersion profile obtained from integrated-light spectroscopy (Lutzgendorf et al., 2011), which is probably affected by shot-noise bias.

of the red giant branch with good signal-to-noise in reasonable exposure times, the horizontal branch level is always brighter than $I = 16.5$ (i.e., all the targets are located at distances < 16 kpc). Moreover, we included only globular clusters with [Fe/H] > −1.8, showing metallic lines deep enough to guarantee a few km s^{-1} accuracy in the radial velocities measurements obtained from low-resolution spectra.

As a first step, the MIKiS survey is expected to provide the full characterisation of the line-of-sight internal kinematics of each target cluster, from the innermost to the outermost regions. Once combined with measurements of proper motion, the global project will provide the full 3D view of the velocity space of each system, obtained from hundreds individual stars, with crucial impact on many hot topics of globular cluster science. In particular, the MIKiS survey will provide:

1. The very first sub-arcsecond kinematic exploration of Galactic globular cluster cores, thus allowing a systematic search for signatures of systemic rotation and intermediate-mass (10^3–10^4 $M_{\odot}$) black holes, providing crucial new insights into the physics and formation processes of both globular clusters and these elusive dark compact objects.
2. The determination of the mass distribution and the global amount of mass in dark remnants (white dwarfs, neutron stars, stellar mass black holes), since the kinematic profiles are sensitive to the whole mass enclosed within stellar orbits. The simultaneous knowledge of the visible matter density distribution and the kinematic profiles can provide reliable estimates of the stellar densities, mass-to-light ratios, and total cluster masses.
3. The exploration of the kinematics in the proximity of the cluster tidal radius, which has major implications for the understanding of the physical origin of recently claimed “extra-tidal structures”, the interplay with the external tidal field, as well as the possible presence of small dark matter halos or modifications to the theory of gravity.
4. A detailed characterisation of the kinematics of multiple populations with different light-element content, to provide crucial constraints to globular cluster formation scenarios.

MIKiS first results

The results obtained so far clearly demonstrate the revolutionary potential of the approach adopted in the MIKiS survey to study the kinematics of collisional systems. In this section, we give an overview of the first set of results. We find that the AO-corrected SINFONI observations attained an angular resolution comparable with that of the HST, thus allowing us to extract individual spectra for 700 resolved stars within 10 arcseconds from the centre of NGC 2808 (see Figure 1), and even 52 individual star spectra within the central 2 arcseconds of the high-density cluster NGC 6388 (see Lanzoni et al., 2013). This is indeed an unprecedented achievement; for the very first time, the radial velocities of hundreds of individual stars have been measured in the innermost core regions of high-density systems, thus finally opening up the possibility of properly exploring the kinematics of Galactic globular clusters at sub-arcsecond scales (see Figures 1 and 4). For comparison, note that no proper motions have been determined in the innermost 10 arcseconds of these dense globular clusters. For example, in the case of NGC 6388, proper motions have been measured at only $r > 20$ arcseconds (Watkins et al., 2015).

Figure 5 summarises the results obtained from the analysis of 6275 stars sampling the entire radial extension of 11 Galactic globular clusters (Ferraro et al., 2018). This dataset allowed us to accurately determine the systemic velocity and velocity dispersion profile of each system, as well as to investigate the presence of ordered motions. It also provides the first kinematical information for two poorly investigated clusters: NGC 1261 and NGC 6496. In the majority of the surveyed systems we find evidence of rotation within a few half-mass radii from the centre. These results are in overall agreement with the predictions of recent theoretical studies, suggesting that the detected signals could be the relics of significant internal rotation that was set at the epoch of the cluster’s formation. This evidence, combined with other recent results in the literature (see for example, Kamann et al., 2018), suggests that the vast majority of Galactic globular clusters (if not all of them) display some level of internal rotation. This might be the remnant signal of a much larger amount of ordered motion imprinted at birth (at the end of the initial violent relaxation phase) which gradually dissipated via two-body relaxation (see Tiongco et al., 2017).

Figure 6 shows the unprecedented rotation curve derived for M5 (Lanzoni et al., 2018a). The velocity dispersion profile and the rotation curve in this cluster were

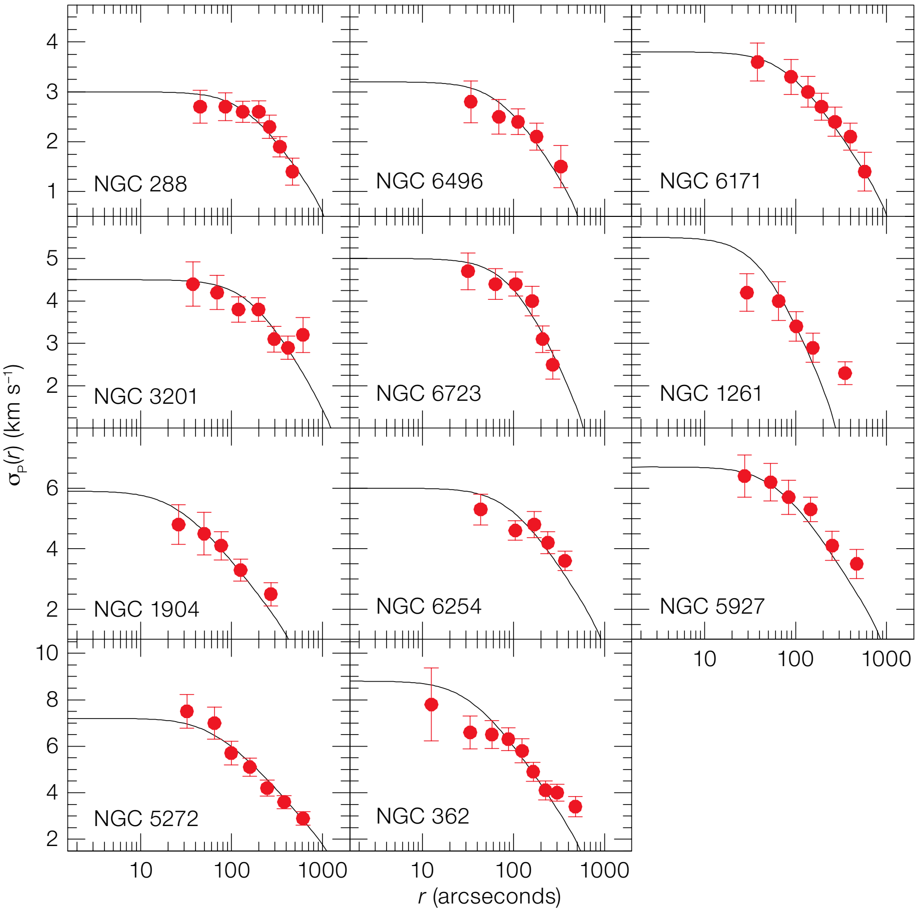

Figure 5. Projected velocity dispersion profiles for 11 Galactic globular clusters observed in the MIKiS survey (red filled circles). The solid lines correspond to the projected velocity dispersion profiles of the King models that best fit the observed density/surface brightness distributions (from Ferraro et al., 2018).

determined from the radial velocity of more than 800 individual stars observed out to 700 arcseconds (~ 5 half-mass radii) from the centre. The rotation curve obtained is the cleanest and most coherent pattern ever observed in a globular cluster. The rotation axis has been measured in distinct concentric annuli at different distances from the cluster centre and it turns out to be strikingly stable (having a constant position angle of 145 degrees with respect to the north-south direction at all surveyed radii). The well-defined shape of the rotation curve is fully consistent with cylindrical rotation. The star density distribution shows a clear flattening in the direction perpendicular to the rotation axis, with the ellipticity (*e*) increasing with increasing distance from the cluster centre, reaching a maximum of *e* ~ 0.14 at *r* > 80 arcseconds. The peak of the projected rotation velocity curve (~ 3 km s^{-1}) has been found at ~ 0.6 half-mass radii, and its ratio with respect to the central velocity dispersion is V_{peak}/σ_0 ~ 0.4. All of these results suggest that M5 is an oblate rotator that is seen almost edge on.

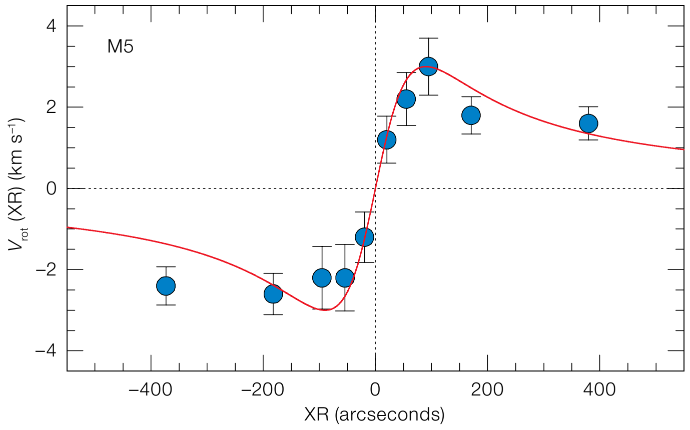

Figure 6. The unprecedented rotation curve obtained for M5 (Lanzoni et al., 2018a). The blue circles mark the mean stellar velocity as a function of the projected distance on either sides of the rotation axis (XR). The red line represents the cylindrical rotation curve, which well reproduces the observed profile.

Figure 7 shows the results obtained in another intriguing cluster: NGC 5986 (Lanzoni et al., 2018b). The velocity dispersion profile (left panel) indicates a significant deviation from the King model in the outer region (*r* > 100 arcseconds) of the system. The clear-cut evidence of systemic rotation is even more impressive. Indeed, the observed rotation curve (right panel of Figure 7) is one of the best examples of solid-body rotation ever found in a globular cluster. This is the first time that these two kinematic features have been jointly observed in a Galactic star cluster, and such co-existence makes the case of NGC 5986 particularly intriguing. In fact, these features may result from the evolutionary interplay between the internal angular momentum of the system and the effect of the tidal field of the host galaxy (Tiongco et al., 2016, 2017). Such a discovery is particularly timely, in light of the growing interest in the physical interpretation of the structure and kinematics of the peripheries of globular clusters and their possible role as new tools for near-field cosmology.

The first results of the MIKiS survey have highlighted the importance of an appropriate search for rotation signals over the entire cluster extension. In fact, the ubiquity of detections of even modest signatures of rotation in globular clusters indicates that most of these systems were born with significant amounts of ordered motion, thus providing significant constraints on globular cluster formation models. On the other hand, the detection of intriguing features, such as those observed in NGC 5986, sheds new light

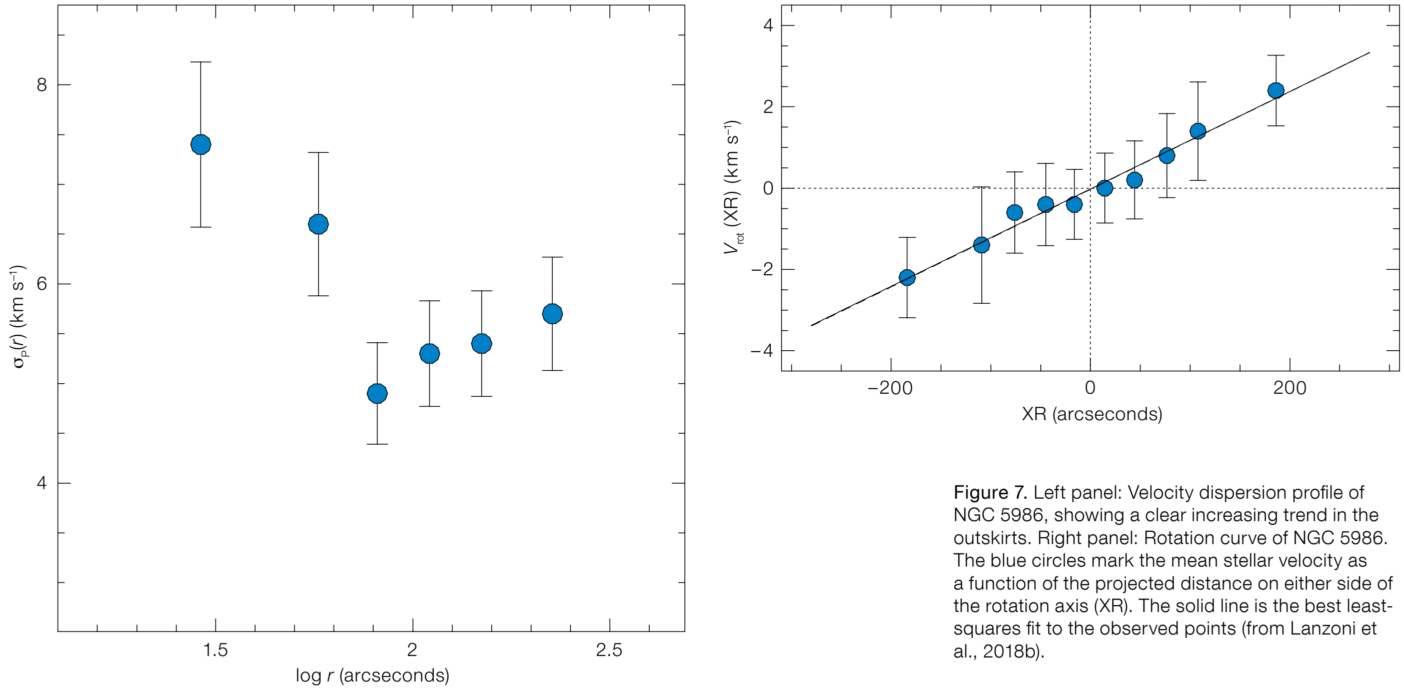

Figure 7. Left panel: Velocity dispersion profile of NGC 5986, showing a clear increasing trend in the outskirts. Right panel: Rotation curve of NGC 5986. The blue circles mark the mean stellar velocity as a function of the projected distance on either side of the rotation axis (XR). The solid line is the best least-squares fit to the observed points (from Lanzoni et al., 2018b).

on the complex interplay between globular cluster internal evolution and the tidal field of the Galaxy.

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Notes

[a] The shape of the profile is fixed by the concentration parameter c, defined as $c = \log(r_t/r_c)$, where r_c is the core radius of the model (roughly corresponding to the cluster-centric distance at which the projected density of stars drops to half of its central value), and r_c is the tidal radius (at which the stellar density becomes zero).

G. Hüdepohl (atacamaphoto.com)/ESO

A drone's eye view of the VLT.

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Constraining Convection in Evolved Stars with the VLTI

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We used the Precision Integrated-Optics Near-infrared Imaging ExpeRiment (PIONIER) at the Very Large Telescope Interferometer (VLTI) to image the stellar surface of the S-type Asymptotic Giant Branch (AGB) star π^1 Gruis. The angular resolution of two milliarcseconds allowed us to observe the surface of this giant star in unprecedented detail. At the observed wavelength the stellar disc appears circular and dust-free. Moreover, the disc is characterised by a few bubbles of a convective nature. We determine the contrast, and the characteristic horizontal length-scale of the convective granules. The latter is determined, for the first time, directly from the image, without involving the usual geometric modelling that has been used in the literature. The measurements fall along empirical scaling relations between stellar parameters and convective sizes, which are determined on the basis of three-dimensional stellar convection models. Our results open up a new era for the characterisation of stellar convection in stars other than the Sun.

The surface of the Sun is populated by about two million convective cells that are roughly 2000 km in size. According to the theory outlined by Schwarzschild (1975), when the Sun evolves towards the red giant branch, its atmosphere will inflate and, because of the lower surface gravity, only a few convective cells will survive at the surface. On the other hand, it is known that stars evolving along the giant branch lose mass via stellar winds. Mass loss from evolved stars is one of the crucial processes for galactic chemistry. Stellar convection is one of the dynamical processes that plays a crucial role in shaping the inner atmospheres of evolved stars. In particular, through its interplay with dust formation, it contributes to the mass-loss process.

The angular resolution of optical interferometry allows the stellar discs of evolved stars to be resolved, as well as smaller structures such as convective granulation. However, for several years we have been limited by the number of available apertures. Several papers have reported asymmetric structures in evolved giants. The departure from spherical symmetry was measured either by comparing visibilities observed at different position angles, or via measurements of closure phase different from zero or ±180 degrees. The observations were then interpreted by superimposing bright spots with varying contrasts on limb-darkened discs (Young et al., 2000; Ragland et al., 2006; Montarges et al., 2016, 2017). In other cases, the interpretation was done using physical models including radiative transfer (for example Cruzalebes et al., 2013, Arroyo-Torres et al., 2015). However, because of the scarce uv coverage, the interpretation of the data was highly non-unique, and asymmetric structures could also be interpreted as indications of the presence of a binary companion (Mayer et al., 2014), or even an increase of the density scale-height in the equatorial plane due to rotation (van Belle et al., 2013). At this stage the need for high angular resolution images became clear.

Stellar surfaces with PIONIER

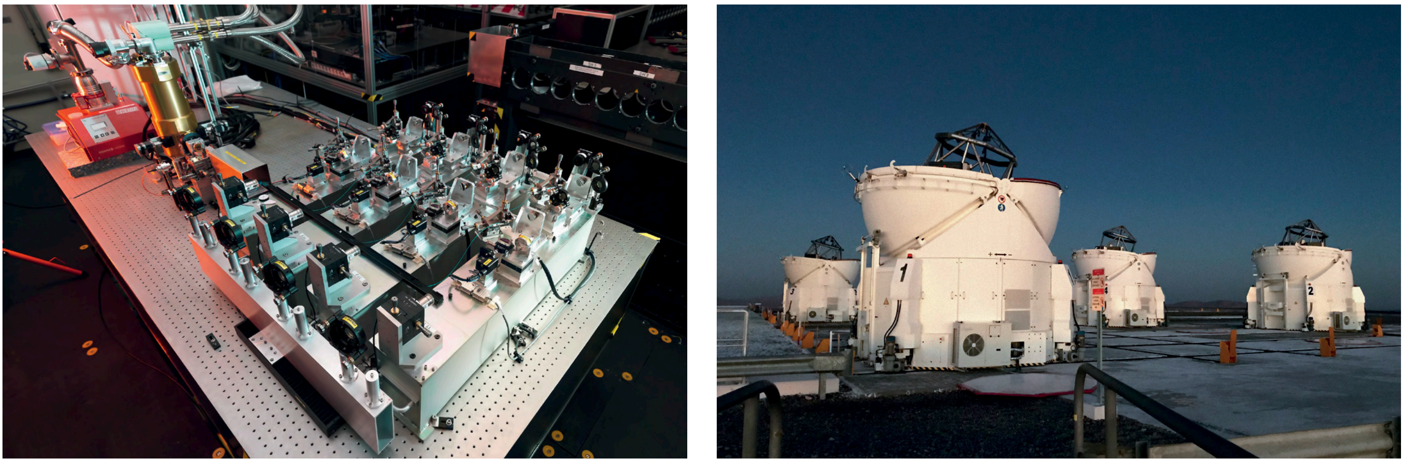
The PIONIER instrument (Le Bouquin et al., 2009) combines the light of four telescopes (the four Auxiliary Telescopes, or the four Unit Telescopes) in the *H*-band. PIONIER is very stable and efficient, and is best suited to imaging bright targets (see for example, Wittkowski et al., 2017).

The semi-regular variable π^1 Gruis, an evolved star with a period of 195 days and a parallax of 6.13 ± 0.76 milliarcseconds, was observed with PIONIER in September 2014 (Figure 1). Given the complexity of the target, we collected as many uv points as possible, which resulted in a total of two nights of observations. The data were obtained using the compact and the medium arrays of the VLTI, which are best suited to imaging targets with a diameter of about 20 milliarcseconds, as in the case of π^1 Gruis. The switch between the array configurations was done within one week to minimise the effect of variability of the star. The *H*-band (like the *K*-band) gives access to the photospheres of evolved stars. AGB stars with oxygen-rich chemistry, such as π^1 Gruis, are ideal candidates for studies of the stellar surface convection, as oxygen-rich dust is transparent at those wavelengths.

We collected 303 spectrally dispersed visibilities (three spectral channels at 1.625, 1.678, and 1.730 micrometers) and 201 closure phases. Model-independent images have been reconstructed for each spectral channel using the software packages SQUEEZE (Baron et al., 2010), and the Multi-aperture image Reconstruction Algorithm (MiRA, Thiebaut, 2008). Figure 2 shows the result of the reconstruction algorithms, which use different principles but give two very robust and similar results in this case. The stellar disc is nearly round, populated by several patterns of a convective nature.

Characterising stellar convection

The three quantities characterising convective granules are the contrast, the size


ESO & B. Lazareff (LAOG)

C. Paladini

Figure 1. (Above) Left: the PIONIER instrument in the VLTI Lab. Right: the four Auxiliary Telescopes in the compact configuration.

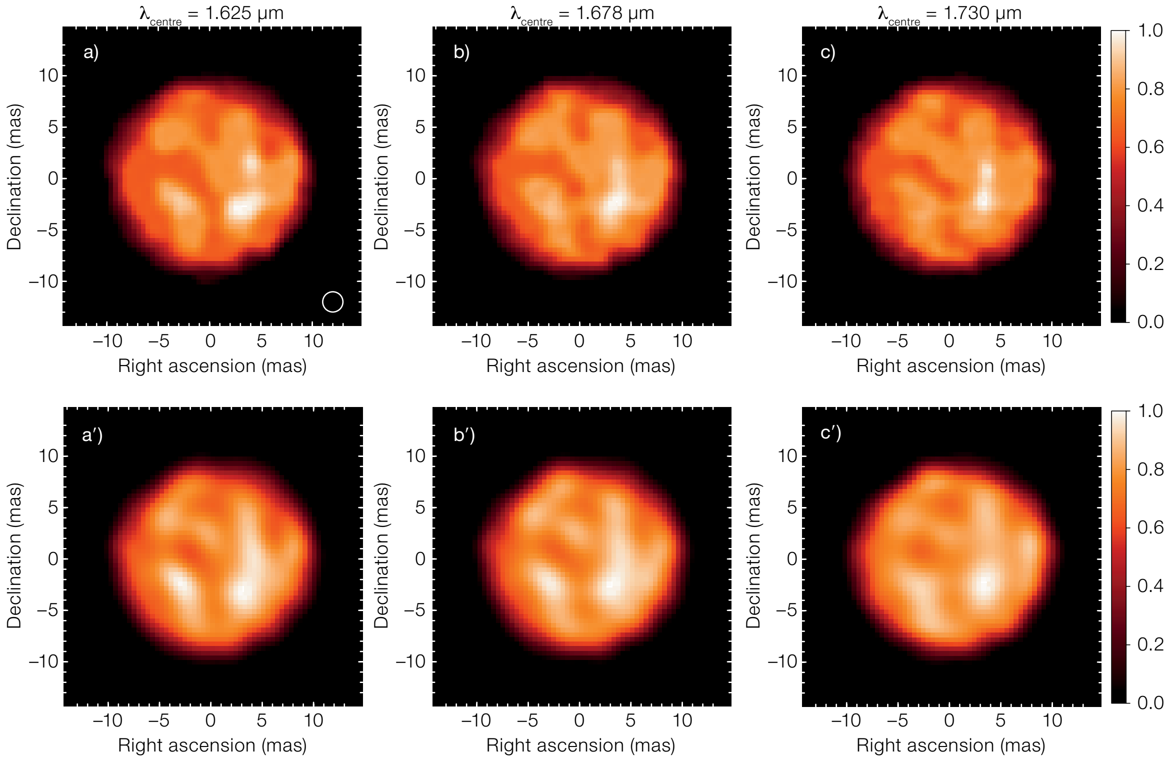


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Figure 2. (Right) Upper panels: the three images in different spectral channels of the surface of π^1 Gruis reconstructed with SQUEEZE. The white circle in the upper left panel represents the angular resolution of the observations. Lower panels: same as above, using the image reconstruction algorithm MiRa.

of the granules, and their characteristic lifetime. The last of these cannot be determined as we currently only have observations obtained at one epoch. The contrast was obtained for every individual spectral channel after correcting the image for limb darkening. We obtained a contrast between 12% and 13%, with a slight increase towards short wavelengths where the contamination from molecular opacities becomes more significant. To derive the characteristic scales of the granules in the images, we did not use any geometric model, but derived the power spectrum density of the image; this method is commonly used in several fields of astronomy, especially when modelling stellar convection. However, a mere power spectrum of our image would simply provide the diameter of the star. As we are interested in the characteristic size of granulation, we subtracted the stellar disc from the image using dedicated masks. Three masks were designed: 1) a limb darkening profile obtained from the Model Atmospheres in Radiative and Convective Scheme (MARCS) model (Van Eck et al., 2017) that best fits the spectral energy distribution; 2) a Gaussian profile; and 3) a square mask that excludes the steep decrease in brightness of the limb darkening in the image.

After subtracting the limb darkening, we scaled the background of the image using the average over the image, and then added space around the image to better isolate the maximum power scale. The resulting power spectrum density is shown in Figure 3. The maximum power corresponds to a typical granulation size of the order of 5.3 (±0.5) milliarcseconds (mas), which corresponds to a linear size of 1.2 (± 0.2) × 10^{11} m at the distance of π^1 Gruis.

Granulation size across the Hertzsprung–Russell diagram

The predictions from a three-dimensional model including convection for AGB stars are still at an exploratory stage. The model grids available in the literature can reproduce solar observations. However, they cover a different stellar parameter space from that of our star (Freytag et al., 1997; Tremblay et al., 2013; Trampedach et al., 2013). Under the assumption that stellar convection works in the same way across the Hertzsprung–Russell diagram, we extrapolated our results and compared the granulation size determined so far with model prescriptions relating the characteristic scale to stellar parameters. Figure 4 shows that our result, represented by the triangle, is well reproduced by the model prescriptions.

Outlook

The next step of this work will be to add the vertical scale information by using the high spectral resolution mode of the VLTI/GRAVITY instrument (Eisenhauer et al., 2011). The characteristic lifetime of convection should involve a monitoring programme that acquires at least an image per month.

A deeper understanding of convection, and how this process depends on stellar parameters, will require extending such studies to several other targets. An imaging survey of AGB stars will be rather straightforward as the VLTI reaches the right angular resolution to resolve the convective granules on the surface of such stars. Given the interplay of convection with pulsation and dust formation, the optimum strategy for future follow up observations would be to use all of the various wavelength bands available at the VLTI — from *H*- to *N*-bands, using PIONIER, GRAVITY, and the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE) — as simultaneously as possible so all the spatial scales could be captured at the same time.

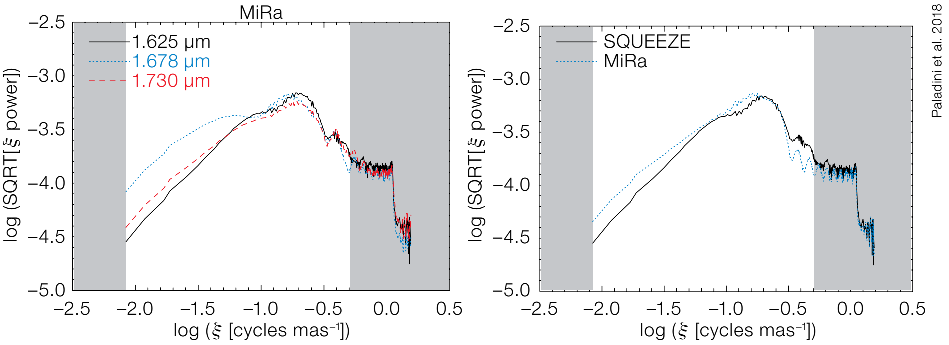

Figure 3. (Left) The power spectrum density of the three spectral channels of the SQUEEZE images. The peaks of the three curves have been averaged after smoothing to derive the power carrying length. The grey shaded area on the left represents the size of the box, while the area on the right is the angular resolution of the observations. (Right) The power spectrum density obtained for the first spectral channel and the two different image reconstruction algorithms.

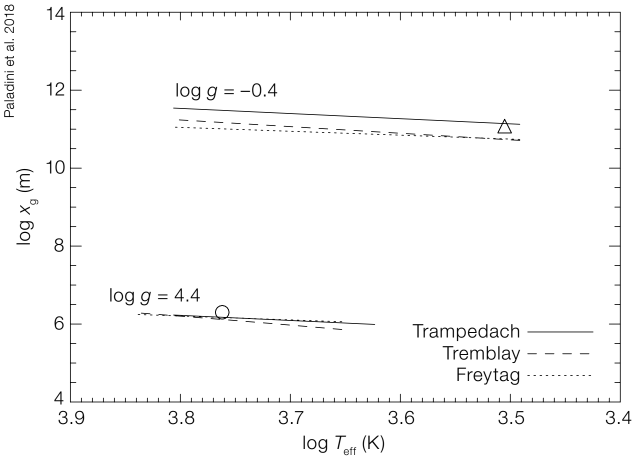

Figure 4. The characteristic granulation size of convection derived from the π^1 Gruis PIONIER images (triangle), compared with theoretical predictions extrapolated from the Sun.

Observations of convective granules for stars less evolved than π^1 Gruis would require higher angular resolution than the one currently available. The latter could be achieved either with longer baselines, or moving to shorter wavelengths.

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A Planet with a Disc? A Surprising Detection in Polarised Light with VLT/SPHERE

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With the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument at ESO's Very Large Telescope (VLT) we can study the linear polarisation of directly detected planets and brown dwarfs, to learn about their atmospheres and immediate environments. We summarise here the recent discovery of a low-mass companion in polarised light by Ginski et al. (2018). The object shows an extreme degree of polarisation, indicating the presence of a circumplanetary disc.

High-resolution polarimetry of substellar companions

In the past 15 years, numerous substellar-mass companions to young nearby stars have been discovered with high-contrast and high-angular-resolution imaging. Using resolved photometry and spectroscopy we can study the atmospheres of these objects, which range from planetary to brown dwarf masses. This makes them especially interesting targets to test planet formation theories. At the same time, the formation of these objects at a few tens or hundreds of astronomical units is particularly challenging, given the limited spatial extent and lifetime of circumstellar discs.

High-spatial-resolution polarimetry is a powerful tool that can provide a plethora of information about these companions. While the thermal emission of substellar objects is not usually intrinsically polarised, scattering by patchy clouds or atmospheric haze can introduce an overall linear polarisation. Rotational flattening, the presence of orbiting moons, magnetic fields, or circumplanetary discs can also cause polarisation. By measuring the degree and angle of linear polarisation with high accuracy we can distinguish between these effects and extract atmospheric parameters as well as information about the circumplanetary environment.

Polarisation has been measured in the past for field brown dwarfs, but only the latest generation of extreme adaptive-optics imagers at large aperture telescopes are allowing us now to open the parameter space to detect these interesting low-mass companions to nearby stars.

The SPHERE instrument (Beuzit et al., 2008) is perfectly suited to this task. Recently van Holstein et al. (2017) were able to constrain the polarisation degree of the planets around HR 8799 to be lower than 1% and the companion to PZ Tel to be lower than 0.1% with measurements performed with the SPHERE Infra-Red Dual Imaging and Spectrograph (IRDIS). Here, we highlight another recent result: the first detection of a new substellar companion to a young nearby star in polarised light.

Observations of the CS Cha system

The CS Cha system contains a spectroscopic binary, both components of which appear to be solar-type pre-main-sequence stars (called T Tauri stars). The system is located in the nearby Chamaeleon I molecular cloud at a distance of 165 pc and was previously studied by means of unresolved photometric measurements, which revealed a large infrared excess. This suggests the presence of a circumstellar disc (see, for example, Espaillat et al., 2007). The observed spectral energy distribution shows a dip at 10 microns, which hints at the presence of a large cavity in the disc, a possible sign of ongoing evolution.

On 18 February 2017 we used SPHERE/IRDIS to observe the CS Cha system in near-infrared polarised light with the aim of resolving its surrounding disc for the first time. Our observation resolved a circumbinary disc with a diameter of ~ 110 astronomical units (au). We show this disc in Figure 1a.

However, the disc was not the only detection made that night. We noticed that a faint companion candidate was visible at approximately 1.3 arcseconds to the west of the primary stars. Remarkably, this companion is not only visible in intensity (see Figure 1c), but also in polarised light (see Figure 1a). It is extremely faint, with an apparent magnitude of 19.2 magnitudes in the *J*-band. Such flux levels are predicted by planetary atmosphere models for objects with a few times the mass of Jupiter. A particularly intriguing property of this companion is its high level of polarisation. In our *J*-band data we measured a degree of linear polarisation of ~ 14%. This value was later confirmed with a follow-up SPHERE/IRDIS observation in the *H*-band.

To prove that the companion is associated with the CS Cha system one needs to measure the common proper motion using archival data. CS Cha was observed with the Nasmyth Adaptive Optics System Near-Infrared Imager and Spectrograph (NACO, Lenzen et al., 2003) at the VLT in the *K*-band 11 years prior to our SPHERE observations. Furthermore, we found *I*-band observations taken in February 1998 with the Hubble Space Telescope's Wide Field and Planetary Camera 2 (HST/WFPC2). Re-reducing these data sets, we were able to recover the companion (see Figures 1 b and e). With a 19-year baseline, we could then show that CS Cha and the companion have nearly the same proper motion on the sky (see Figure 2). The small differential motion that we found is consistent with the orbital motion that is expected for a low mass companion. This makes it very likely that this object is gravitationally bound to CS Cha.

The next step in our analysis was to investigate the possible causes for the high degree of polarisation. One possibility could be the presence of a large amount of interstellar dust between the Solar System and the CS Cha system. This would be especially likely if CS Cha is located deep within the Chamaeleon I molecular cloud. We measured the degree of polarisation of the unresolved primary stars in our *J*- and *H*-band SPHERE data sets and found that their light was polarised to less than 1%. This strongly suggests that the degree of polarisation of the companion is intrinsic and not caused by interstellar dust.

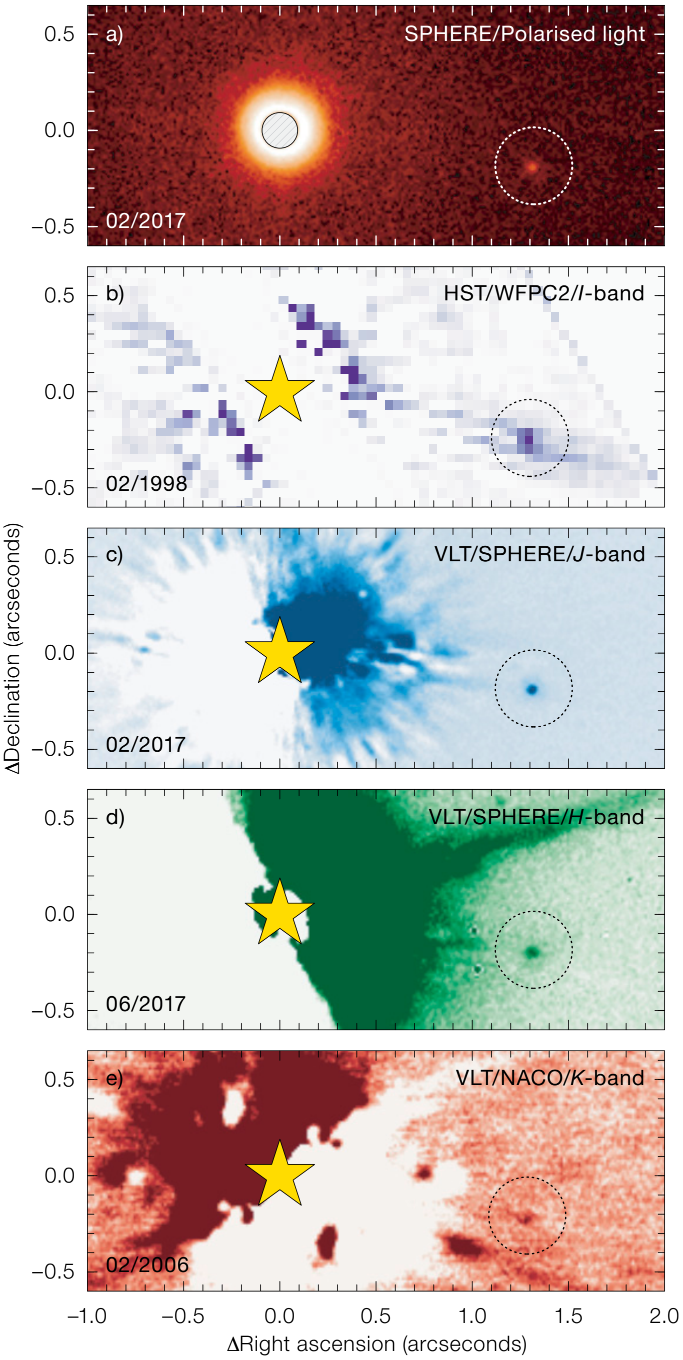

Figure 1. Observations of the CS Cha system at multiple wavelengths and with various instruments. The companion is always marked by a dashed circle. (a) SPHERE polarised light image. The companion is seen in polarised light along with the disc around the central binary star. The coronagraph that was used is indicated by a grey hatched circle. (b–e) Total intensity unpolarised images of the companion. The stellar PSF was partially subtracted to increase the companion contrast, also creating the dark-bright patterns visible. The position of the central binary is marked with a star symbol.

A planet with a disc?

Since we have multiple observations of the companion in various photometric bands we can attempt a characterisation. In particular, we are interested in constraining its mass and determining the causes of its high degree of polarisation.

In Figure 3 we show all the available photometric measurements along with upper limits for non-detections. We always measure the companion magnitude relative to the host star. We then use the known brightness of the host to translate these relative measurements into absolute fluxes. The SPHERE *H*-band photometry has larger uncertainties because the observations were taken in poor weather conditions.

We compared the companion photometry to PHOENIX (Helling et al., 2008) atmosphere models for substellar objects. In Figure 3, we show two model spectra, obtained for an object of 5 Jupiter masses (M_{Jup}) and one of 20 M_{Jup}. These model spectra include clouds in the atmosphere models, but do not include circumplanetary material.

We found that the *J*-*H* colour of the companion is somewhat consistent with a

$5\text{-}M_{\mathrm{Jup}}$ planet. However, the model spectrum overpredicts the flux in the NACO *K*- and *L*-bands and underpredicts it in the HST *I*-band. A $20\text{-}M_{\mathrm{Jup}}$ planet, on the other hand, completely overpredicts the flux across all photometric bands. We conclude that no standard atmosphere model could reproduce these peculiar photometric measurements. Additionally, clouds in planetary atmospheres are not expected to cause linear polarisation of more than a few percent (Stolker et al., 2017).

The presence of a circumplanetary disc seen at a high inclination, i.e., close to edge-on, can produce a high degree of linear polarisation in the companion. Such a strongly inclined disc would then also block some of the light from the companion itself. This would naturally explain why "naked" planetary atmosphere models are a bad fit to the available photometry. We can put one further constraint on a potential circumplanetary disc. It needs to be small enough that we are not able to resolve it in our SPHERE images. This means that its diameter must be less than 4 au.

After some first attempts at modelling the observations we realised that an inclined disc alone still does not explain the high degree of polarisation. In fact, our models underpredict the degree of polarisation by a few percent and do not fit the photometry. However, if we include a very thin dusty halo, then we can nearly reproduce all of the measurements. This halo has a dust mass two orders of magnitude less than that of the disc itself. We show the best-fitting models in Figure 4. For simplicity, each model is computed for a single dust grain size only. The models with 0.1- and 1.0-micron particle sizes reproduce the companion photometry well. The smaller grains, on the other hand, lead to an overprediction of the degree of polarisation, while the larger grains slightly underpredict the polarisation, especially in the *J*-band. It is thus reasonable to assume that a more complex mixture of differently sized grains should be able to reproduce the measured polarisation.

Since the flux of the companion is attenuated by its surrounding disc, we need a higher-mass object to fit the photometry

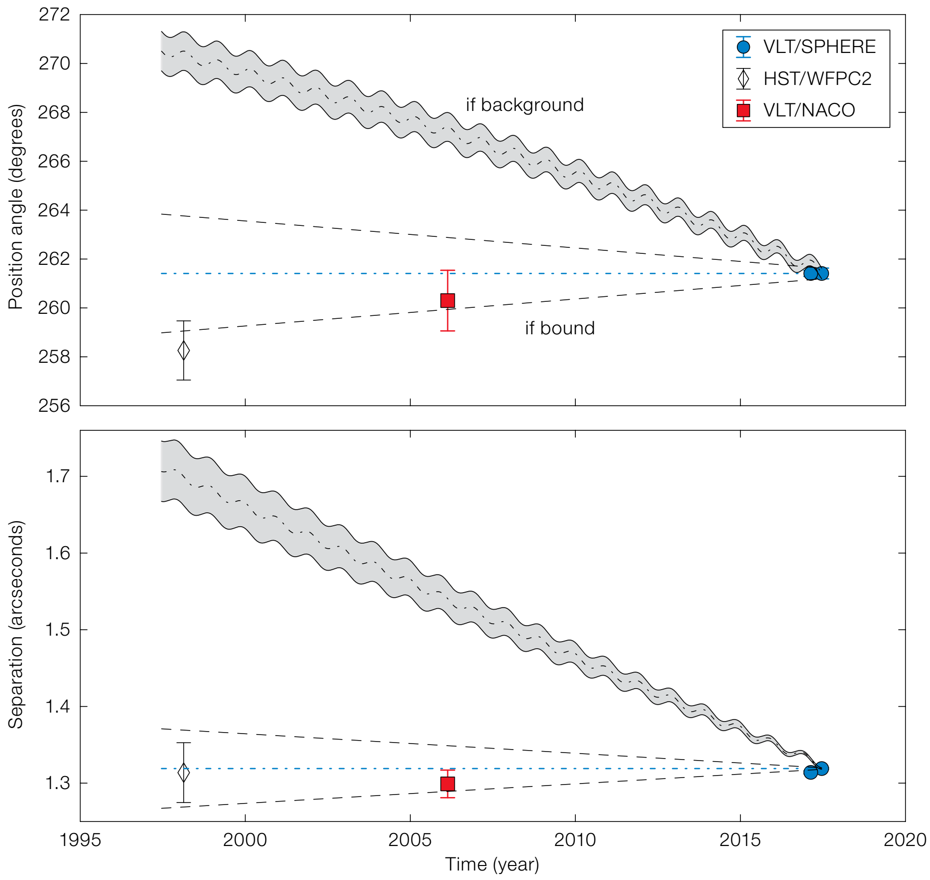

Figure 2. (Above) Astrometric measurements of the companion relative to the unresolved primary stars. The grey "wobbled" area is the area where background objects would be expected, while the area between the dashed lines is where gravitationally bound objects are expected.

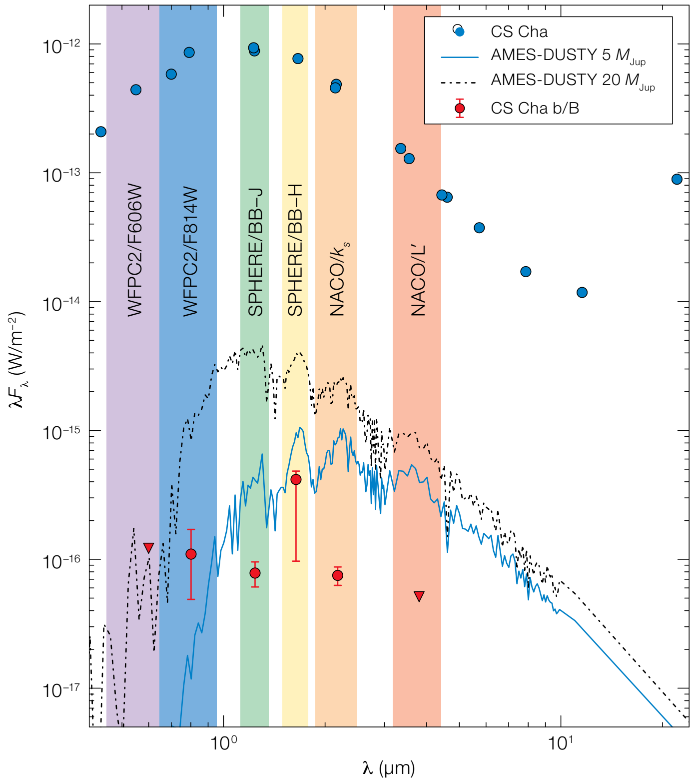

Figure 3. (Left) Photometric measurements (circles) and upper limits (triangles) of the companion (red symbols) in different bands and with different instruments. For comparison we also plot the photometry of the unresolved primary stars (blue symbols), as well as theoretical models for a $5\text{-}M_{\mathrm{Jup}}$ and a $20\text{-}M_{\mathrm{Jup}}$ planet (solid and dashed lines).

compared to the "naked" atmosphere models. In this case we use a 20-M_{Jup} planet.

These first models fit well with the measurements, but they still suffer a degeneracy between the mass of the central object, the inclination of the circumplanetary disc and the dust grain sizes. Therefore we caution that the solution we find is likely not the only one. However, since the modelled disc inclination of ~ 80° is rather high, we can be sure that the companion is not significantly more massive than our current estimates. More massive central objects would require a stronger attenuation to fit the photometry and thus a higher disc inclination.

We show a schematic of the full CS Cha system in Figure 5 as described in our model. The elevation of the companion along the line of sight is unknown, so we do not know if it is partially illuminated by the central binary, or completely shadowed by the circumbinary disc. We conducted tests to investigate the possibility of additional illumination of the companion by the central binary and found that this had only a marginal effect on our modelling.

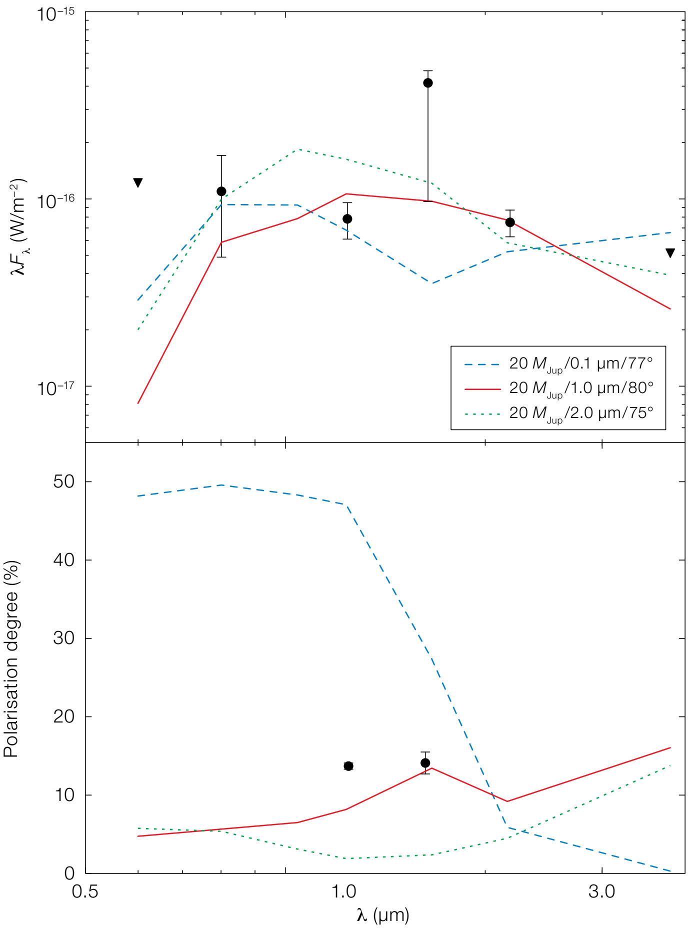

Figure 4. (Left) Companion photometry and degree of linear polarisation along with our best fitting models. Different colours and line styles denote different inclinations of the circum-companion disc as well as different dust grain sizes. Triangles show upper limits, while circles are current measurements.

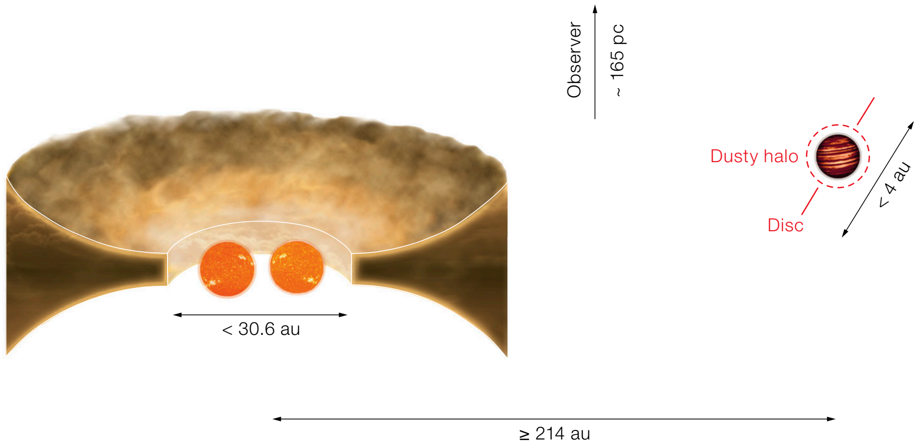

Figure 5. (Below) Schematic of the CS Cha system. Distances and sizes are not to scale.

Planet formation in the CS Cha system

Given what we know about the CS Cha system, we can speculate on how the companion may have formed. The circumstellar disc that we detected in polarised scattered light only extends out to ~ 55 au. It is possible that the disc extends further, but we do not see it in scattered light because it is partially self-shadowed. However, it seems unlikely that the disc extends out to the companion position at 214 au.

Given the available astrometry, we computed possible orbits of the companion. We found that orbits that are circular and co-planar with the circumstellar disc do not fit the available data. We further find that the companion's orbit must be at least slightly eccentric if the companion mass is indeed as low as our modelling work predicts. The orbital plane is likely misaligned with the plane of the circumstellar disc and thus with the spin axis of the primary stars. Furthermore, the circumplanetary disc may be misaligned with both the orbital plane and the stellar spin axis. Such misalignments would not be predicted if the companion formed in the disc around the primary stars. Thus we speculate that the companion may have formed as a component of a multiple stellar system. In multiple stellar systems such misalignments are quite common (see, for example, simulations by Bate, 2012).

In the future we will need follow-up observations with the Atacama Large Millimeter/submillimeter Array (ALMA), to constrain the dust mass around the companion as well as the extent of the gas disc of the stellar spectroscopic binary. Also, spectral observations in the near-infrared are needed to better characterise the companion. In particular, we will need (HST/WFC3) observations as the limitations of current ground-based instruments do not allow us to detect the spectrum of the companion.

The CS Cha system offers concrete evidence of a formation pathway for wide planetary-mass companions and shows the power of polarimetry as a tool for planet characterisation.

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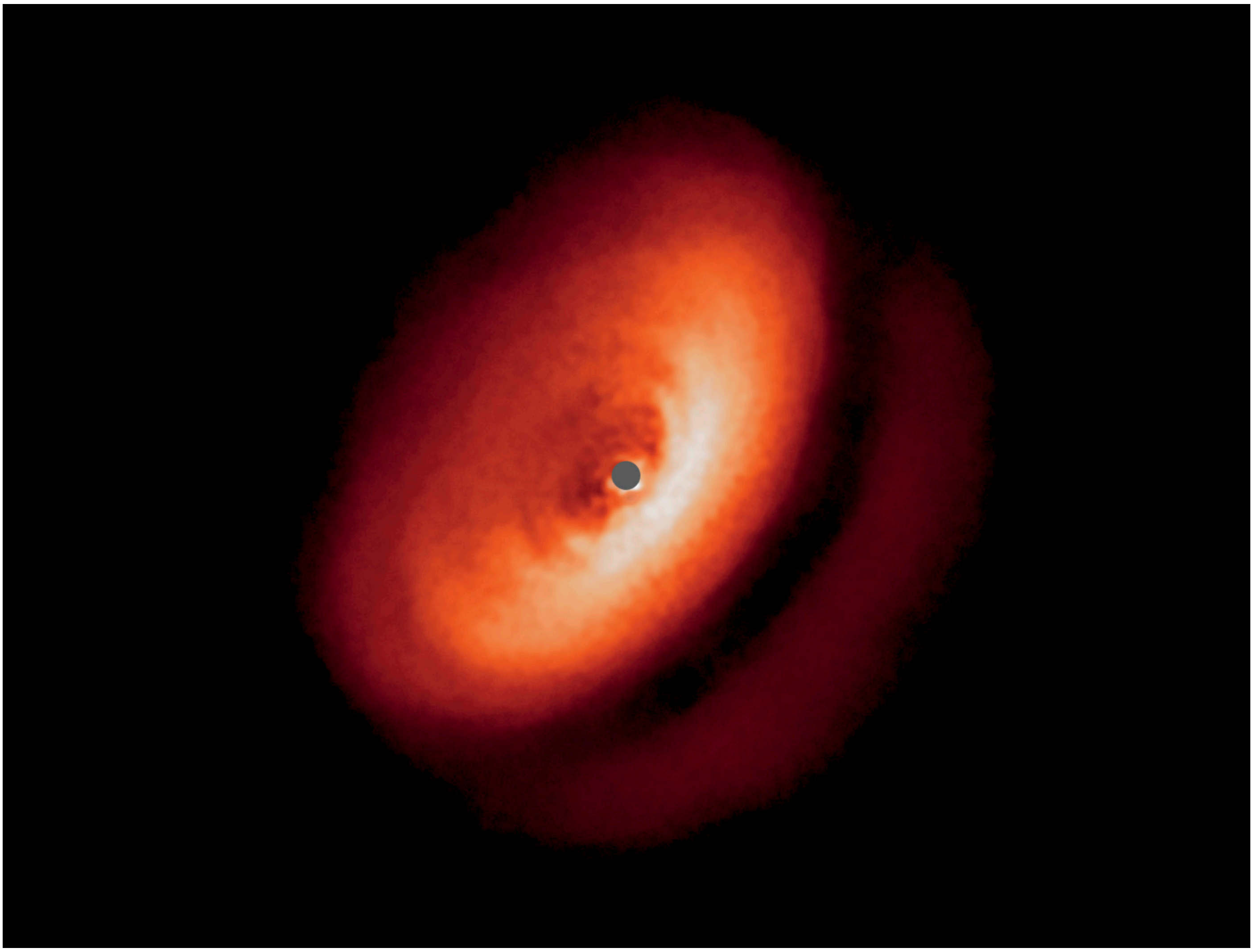

ESO/H. Avenhaus et al./DARTT-S collaboration

SPHERE image of the enormous dust disc surrounding the T Tauri star IM Lup.

ESO/P. Horálek

Upper: A planetarium show at the ESO Supernova Planetarium & Visitor Centre, which opened its doors to the public on Saturday 28 April 2018.

Lower: ESO and VDL ETG Projects B.V. (the Netherlands) sign a contract for the manufacture, assembly, testing and delivery of the Segment Support Mechanics, responsible for holding and controlling the 798 mirror segments of the primary mirror of the Extremely Large Telescope.

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Report on the ESO Workshop

Planning ESO Observations of Future Gravitational Wave Events

held at ESO Headquarters, Garching, Germany, 31 January–1 February 2018

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Ferdinando Patat[1]

[1] ESO

Understanding the nature and results of black hole and neutron star mergers has become a hot topic in astrophysics. The combination of gravitational wave and electromagnetic observations of GW170817/GRB 170817A has triggered new and exciting science projects. The timeline for observations of gravitational wave events lies between seconds and days, and coordinated observations of electromagnetic radiation are critical when probing the nature of these events. The great success of the observations of GW170817/GRB 170817A from more than 50 observatories has highlighted the importance of coordination between different instruments and facilities. This two-day workshop focused on what has been learned from ESO observations of GW170817/GRB 170817A, and discussed strategies for coordinating observations of future events.

Background

The first detection of an electromagnetic counterpart of a gravitational wave event had a historic dimension, as it connected two seemingly separate "universes". Several mergers of black holes had been observed prior to that, indicating black holes of several tens of solar masses; this presented a puzzle, as black holes of these sizes had not previously been anticipated. The detection of gravitational waves — a technical feat requiring measurements of strains of a few times 10^{-20} — in 2015 was epochal, and was recognised with the Nobel Prize in Physics in 2017. While black hole mergers are not expected to carry an electromagnetic signal, theoretical modelling predicted that the merger of two neutron stars would lead to short gamma-ray bursts (GRBs), and would potentially be site of the formation of heavy elements through the *r*-process.

When, on 17 August 2017, an unusal gravitational event (GW170817) was observed that coincided with a short gamma-ray burst (GRB170817A) two seconds later, the search for an optical/infrared counterpart was on. Within a few hours, an optical counterpart was detected in the galaxy NGC 4993. Spectroscopic follow-up observations began immediately, resulting in a detailed record of the evolution of the event over the following two weeks.

ESO and ESA telescopes and instruments participated in this global observing campaign. Parts of the community focused on the search of the optical counterpart with ESO's Visible and Infrared Survey Telescope for Astronomy (VISTA) and the VLT Survey Telescope (VST), but as soon as the GRB detected by the ESA INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite and its optical counterpart had been identified, the event was followed up using several spectrographs and imagers.

Workshop goals

The goal of the workshop was to bring the community together to discuss the best way to obtain ESO observations of future gravitational wave events. Despite the speed with which the workshop was organised — it was announced in the ESO Science Newsletter on 20 December 2017 — 55 participants had registered by the deadline in early January.

The speaker list was partially defined through the Principal Investigators (PIs) of exisiting proposals. Eight of the 26 speakers were female (corresponding to 31%), which reflected the gender distribution amongst the registered participants (29% female). The first day of the programme was dedicated to assessing the status of the gravitational wave detections and their follow-up observations, in particular for GW170817; while the second day focused on the planning and coordination of future observations. Each day finished with an extensive discussion session. On 31 January, the past and current ESO observations of (fast) transients were discussed, and potential lessons for future observations debated. The afternoon of 1 February was entirely devoted to a community discussion of the best strategies for future electromagnetic observations of gravitational wave events. The programmatic aspects of ESO observations were also exhaustively explored.[1]

The first session was focused on GW170817 observations. The gravitational wave signal was presented and compared to that from black hole mergers by Sarah Antier (Laboratoire de l'Accélérateur Linéaire Orsay), followed by a description of the event as seen at optical and near-infrared wavelengths (Stephen Smartt, Queen's University Belfast), in X-rays (Maria Grazia Bernardini, Laboratoire Univers et Particules de Montpellier) and in gamma rays (Roland Diehl, Max Planck Institute for Extraterrestrial Physics [MPE] in Garching).

Marina Rejkuba (ESO) reported on the ESO observations and the activities associated with the release of the data to the community. Optical observations of GW170817 could only be conducted for a couple of hours before the object set each evening in Chile, with several instruments being used simultaneously on the VLT. The ESA satellites INTEGRAL and X-ray Multi-Mirror satellite (XMM-Newton) also participated in the observing campaign, and Peter Kretschmar (European Space Agency, ESA) gave an account of the activities required at the operations centres in order to obtain these data at short notice.

Since it is still very early days for the electromagnetic observation of gravitational wave events, Anders Jerkstrand (Max Planck Institute for Astrophysics, Garching) gave a theorist's view of what we should expect and how to make sense of the observations of GW170817. He gave a comprehensive overview of what the signatures of the *r*-process elements would look like in the optical and near-infrared spectral sequences, and outlined where we still have significant gaps in our interpretation of the spectra. There remains plenty of room for future observations to clarify the many questions and uncertainties we still have in respect of these events. The session ended with a presentation by Nial Tanvir (University of Leicester) on his experience of ESO observations of fast transient phenomena, focusing on gamma-ray bursts. Target of Opportunity observations have been offered at the VLT since the beginning of operations, with the addition of refinements such as the rapid response mode about 10 years ago. This frank presentation was an excellent basis for a discussion on how ESO operations could help to secure critical data for similar events in the future.

The afternoon session was reserved for presentations of ongoing projects dedicated to the follow-up of transient events. ESO is supporting several such programmes, either with its own telescopes or by hosting dedicated experiments at its sites. These include the following projects: the public survey called VIsta Near-infraRed Observations Unveiling Gravitational wave Events (VINROUGE), which uses VISTA to obtain infrared light curves (Andrew Levan, University of Warwick); the extended Public ESO Spectroscopic Survey of Transient Objects (ePESSTO), which uses the ESO Faint Object Spectrograph and Camera 2 (EFOSC2) at the New Technology Telescope (NTT) to provide optical spectroscopy (Maria Teresa Botticella, INAF–Osservatorio di Capodimonte); the Rapid Eye Mount telescope (REM) at La Silla, which is part of a larger collaboration set up to follow the optical counterparts of gravitational wave events (Eliana Palazzi, INAF–IASF Bologna); and the Gamma-Ray burst Optical/Near-infrared Detector (GROND) instrument on the Max-Planck-Gesellschaft/ESO 2.2-metre telescope at La Silla, which obtains photometry in seven filters simultaneously (Janet Chen, MPE Garching).

A new project that is just starting operations is the Gravitational-wave Optical Transient Observer (GOTO), which was described by Danny Steeghs (University of Warwick). In addition, the long-running Télescopes à Action Rapide pour les Objets Transitoires (TAROT) project was presented by Michel Boer (Centre National de la Recherche Scientifique, CNRS). Future facilities to detect and characterise the electromagnetic counterparts of gravitational wave events are: BlackGEM, to be installed at La Silla (Paul Groot, University of Nijmegen); the Son Of X-Shooter (SOXS), to be installed on the NTT in 2020 (Sergio Campana, INAF–Osservatorio Astronomico di Brera); and the Zwicky Transient Facility in California (Ulrich Feindt, Oskar Klein Centre Stockholm).

The discussion session covered past ESO observations, and aimed to identify what worked and where difficulties were encountered. The panel members were Stefano Covino, Marina Rejkuba, Steven Smartt and Nial Tanvir. The open discussion yielded some interesting comments, and comparisons were made with the experience of using ESO telescopes for observations of gamma-ray bursts. It was concluded that overall ESO provided valuable — and sometimes unique — resources that can be essential, providing insights in areas where theoretical predictions are lacking. Recommendations were made to strengthen the communications between various observatories and facilities in order to avoid duplication and to increase synergies.

The second day of the workshop concentrated on the planning of future observations. The schedule of science observations with the Laser Interferometer Gravitational-wave Observatory (LIGO)-Virgo collaboration was presented by Marica Branchesi (Gran Sasso Science Institute). The next science run is planned to start in October 2018 and is scheduled to last for approximately one year. The principal investigators of the current ESO programmes to search for and follow up electromagnetic signals from gravitational wave events then presented their plans for the next semester. Elena Pian (INAF–IASF Bologna) and Paolo D'Avanzo (INAF–Osservatorio Astronomico di Brera) presented their VLT proposals. A proposal to obtain spectropolarimetry of such events was detailed by Stefano Covino (INAF–Osservatorio Astronomico di Brera). Aniello Grado (INAF–Osservatorio Capodimonte) then presented two ongoing programmes with the VST.

A special session on the observing opportunities with ESA satellites followed. The capabilities of INTEGRAL, and in particular its operational constraints, were introduced by Erik Kuulkers (ESA), followed by a presentation on XMM-Newton by Norbert Schartel (ESA). Jan-Uwe Ness (ESA) described some programmatic aspects of the planning and coordination of space-based observations. The INTEGRAL and XMM-Newton schedules are built well in advance of he observations and the rapid observation of an unexpected transient may mean a serious interruption to the uploaded schedule, requiring the corresponding recovery of the schedule timeline afterwards. There may also be pointing constraints for satellites which need to be evaluated before schedule interruptions. Aitor Ibarra (ESA) and Richard Saxton (ESA) set out a new tool for the improved coordination of observations and information sharing.

The afternoon was devoted to a discussion centred on the optimal planning of future observations, including the best possible coordination of ESO telescopes and instruments. Ferdinando Patat, Enzo Brocato, Peter Jonker and Erik Kuulkers were the panel members, and a lively discussion ensued between the panel and the audience. Several important points were raised, among them the wish that ESO accept Large Programmes with Target of Opportunity observations. Additionally ESO was asked to provide rapid delivery of pre-reduced data so that quick assessments and scientific decisions can be made, potentially to then interactively modify observation blocks for follow-up observations. ESO will have to investigate which of these requests can be implemented operationally. As a first step, Target of Opportunity Large Programmes were accepted again for ESO Period 102 (from October 2018 to March 2019). An important discussion point was whether the (European) community could agree to submitting a single ESO proposal for observations of future gravitational wave events. As a result of this discussion one single Period 102 proposal was submitted before the deadline of 28 March 2018. ESO was also invited to attend the LIGO–Virgo town hall meeting in April 2018 in Amsterdam, where these discussions will continue.

Acknowledgements

We thank Svea Teupke for providing logistical support at very short notice. We would also like to thank all of the speakers for providing the slides ahead of their presentations so that a seeing-impaired colleague could follow them on his own laptop.

Links

[1] Workshop programme: http://www.eso.org/sci/meetings/2018/gw2018.html

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Report on the ESO Workshop

Imaging of Stellar Surfaces

held at ESO Headquarters, Garching, Germany, 5–9 March 2018

Markus Wittkowski[1]
Liz Humphreys[1]

[1] ESO

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

Figure 1. Conference photo.

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

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

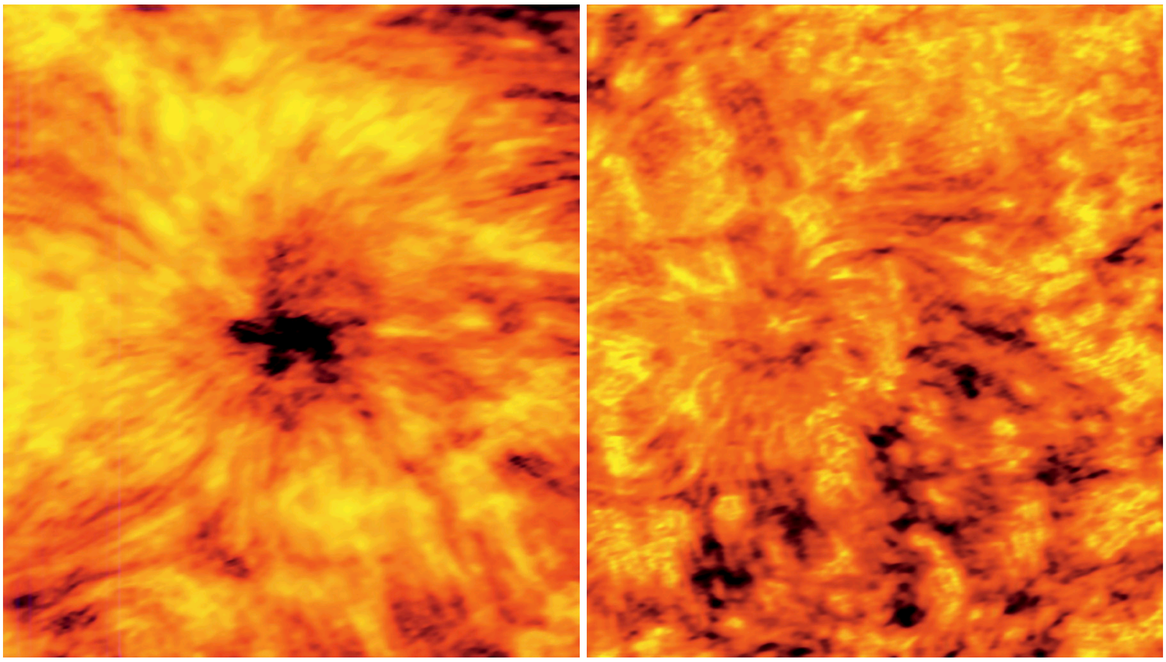
The VLT instrument Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) is also resolving the surfaces of the some of the largest stars. At the same time, ALMA observations using long baselines have succeeded in resolving stellar surfaces at millimetre wavelengths. A number of other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

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

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

The Sun as a star

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



ALMA (ESO/NAOJ/NRAO)

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

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

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

From the Sun towards evolved stars

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

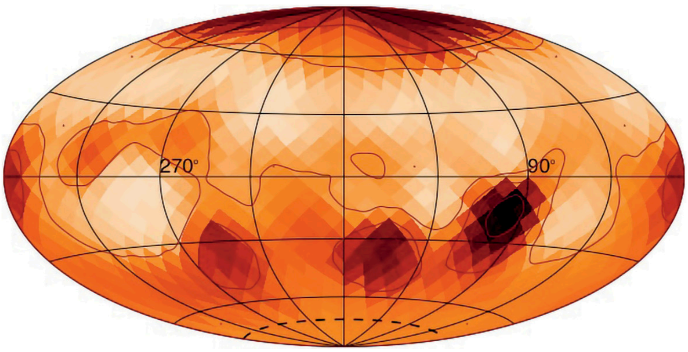
Agnes Lèbre (in an invited talk), and the next speakers described the techniques and recent results from spetropolarimetry, detecting magnetic fields and star spots on the surfaces of Sun-like stars (Emre Isik, Torsten Böhm) a giant and supergiant stars (Agnes Lèbre, Arturo López Ariste). Susanne Höfner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

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

Imaging results

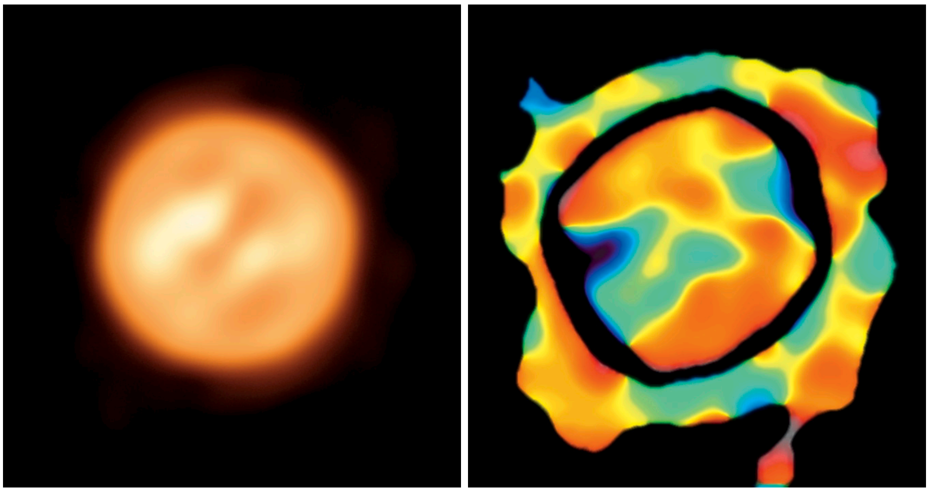
A major theme of the meeting centred on recent imaging results of stellar surfaces obtained at visible/infrared and radio/millimetre wavelengths, and comparing them with models and other complementary observations. Gail Schaefer started this session by providing an invited overview on imaging stellar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

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



Roettenbacher et al., 2016

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



ESO/K. Ohnaka

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

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

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

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

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

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

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

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

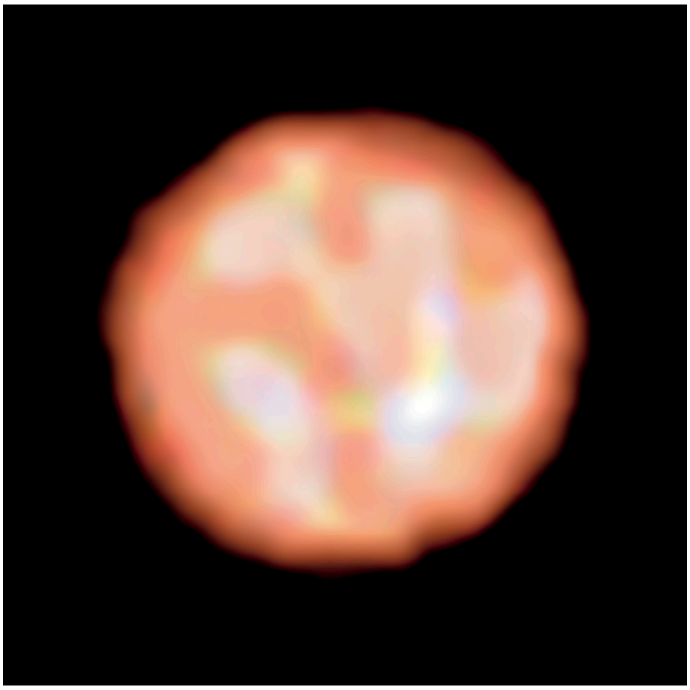

ESO/C. Paladini

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

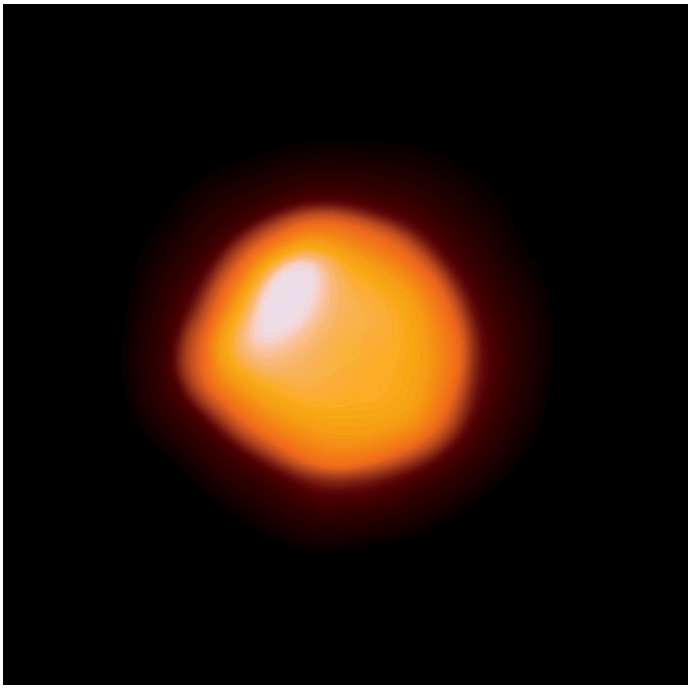

ALMA (ESO/NAOJ/NRAO)/E. O'Gorman/P. Kervella

Figure 6. Betelgeuse, as captured by ALMA.

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

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

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

Image reconstruction techniques

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

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

Prospects

Gioia Rau started the session on future prospects with an invited talk about imaging the surfaces of stars from space. She reviewed results obtained so far from space with the benefit of extending the wavelength coverage, including ultraviolet spectra taken with the International Ultraviolet Explorer (IUE), as well as ultraviolet images obtained with the Hubble Space Telescope (HST) of Mira and Betelgeuse. She then investigated the prospects for infrared imaging with the James Webb Space Telescope (JWST), and finished with a forward look towards space-based large-baseline Fizeau interferometers such as the ultraviolet-optical Stellar Imager (SI) Vision Mission.

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

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

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

Main conclusions and the way ahead

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

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

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

Demographics

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

Acknowledgements

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

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Links

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

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Report on the Workshop

Dispersing Elements for Astronomy: New Trends and Possibilities

held at the Civic Aquarium of Milan, Italy, 9–11 October 2017

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Rebecca Bernstein[2]
Antonio de Ugarte Postigo[3,4]
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[7] ESO
[8] NOVA Optical Infrared Instrumentation Group, ASTRON, the Netherlands

Astronomical spectrographs play an important role in addressing some of the biggest challenges in modern astronomy. One of the most critical components of any spectrograph is its dispersing element, since it determines the resolution and dispersion of the spectrograph, and is typically one of the least efficient optical components of the instrument. The aim of this workshop was to bring together researchers and engineers involved in the design, development and construction of spectroscopic instrumentation, with companies and institutes that produce dispersing elements and associated optical components. The forum provided the opportunity to discuss the scientific needs of future instruments, and to address the technological challenges that will allow the development of new types of dispersing elements in the coming years.

In order to adequately address open questions in astronomy, there is a drive for the development of bigger, more sensitive telescopes and instruments — both ground-based and in space — with a very wide spectral range. In respect of ground-based facilities, the current Extremely Large Telescope (ELT) projects provide clear evidence for this, and spectrographs play an essential role in their planned instrument suites. Dispersing elements are at the core of these instruments, since they define the spectral resolution and dispersion of the spectrograph and hence the final performance of the instrument. On the other hand, because of their nature, dispersing elements are often the least efficient optical elements of the whole spectrograph, and therefore dominate the final instrumental throughput. This, of course, also holds true for smaller telescopes, which can typically address a broad range of science cases provided they have adequate instrumentation.

Starting from the design phase of any spectrograph, it is crucial to be aware of the different possibilities that are available on the market, including those that have not specifically been developed for astronomy. Indeed, thanks to new technologies, the possibilities in the field of diffraction gratings and dispersing elements are increasing as a result of a number of different approaches, for example, holography, lithography and micro-machining. This is not always easy, since the requirements can vary across different fields. However, it can be possible to adapt the latest technological advances to specific scientific needs. On the other hand, it is also important for companies and research institutes that are active in the design and production of dispersing elements, and that are involved in the design of the spectrographs, to understand how to adapt technological developments towards becoming feasible products for astronomical research.

This workshop[1] brought together researchers and engineers involved in the design, development and construction of spectroscopic instrumentation, as well as companies and institutes that produce dispersing elements and associated optical components. The forum provided an opportunity to discuss the scientific needs of current and future instruments and to address the technological challenges that will enable the community to progress with the development of new types of dispersing elements in the coming years.

The focus was mainly on dispersing elements based on gratings and prisms; alternative approaches such as Fabry-Perot interferometry or Fourier-transform spectrometers were not considered. The workshop was organised into the following three main sessions:

- An overview of the scientific questions to be addressed, both with large and small ground-based astronomical facilities. In this session, the status of the three ELTs currently under construction was presented, including their instrumentation programmes.
- Properties of dispersing elements for astronomy, their evolution, the issues and constraints of the optical design of spectrographs for large telescopes and, finally, their calibration.
- Technologies for the production of gratings and prisms. This session was divided according to the different manufacturing technologies and spectral range of use of the diffractive elements.

Discussions and outcomes

In general, the instrumentation suites proposed for the three ELT projects are similar, and require a wide range of spectral and spatial resolutions. They resemble the instruments developed for the 8–10-metre-class telescopes and all face the challenges of wide focal planes and the conservation of the "étendue" — a property of the light used to characterise the area and angle over which it is spread out. Large-sized gratings/prisms are required to reach the target resolution, but it is important to keep the total size of the instrument within bounds by means of strategic choices in the optical design (through pupil and image slicing).

The 8–10-metre-class telescopes will require new instrumentation and new concepts in the era of the ELTs. One example may be the efficient spectroscopic telescopes currently under study, which are designed to simultaneously collect thousands of spectra of targets that are fed from wide field surveys. The same approach applies to small- and medium-class telescopes, where the scientific cases are often diverse, and which may also need to develop or focus on specific science cases with very efficient, dedicated instruments.

Figure 1. Workshop participants.

The dispersing elements for the spectrographs have a large set of requirements. Aside from achieving the highest possible diffraction efficiency, it is also important to understand and know their dispersion, price, weight/size, availability on the market, ghosts, wavefront error (WFE), etc. Being able to obtain repeatable and consistent wavelength calibrations is essential to get the best out of the spectrographs, especially for highly stable high-resolution spectrographs.

The different technologies discussed at the workshop related to the manufacture of diffraction gratings can be summed up under the following headings.

High-performance first-order diffraction gratings

Volume Phase Holographic Gratings (VPHGs) are considered the baseline for instrumentation in the visible and near-infrared bands, on the basis of the excellent results obtained over the last decade. However, some limitations were apparent, such as their size, WFE, and their efficiency at high dispersion. Other techniques are becoming available, in particular lithographic gratings based on either electron-beam lithography or on holography. There are some degrees of freedom in the structure of the periodic pattern and in the material, which allow for the maximisation of the diffraction efficiency — even in the ultra-violet. As there are markets that require such gratings in very large formats, it is now feasible to reach sizes of the order of a square metre, and these possibilities are worth considering when designing future instrumentation.

Dispersing elements for the infrared

In the infrared, immersed gratings have become an interesting option since the availability of materials with high refractive index makes it possible to increase the resolution significantly while keeping the size under control. Moreover, other technologies, such as VPHGs, are not suitable for wavelengths above 2.5 μm (new approaches based on direct laser inscription are being developed to extend the range to longer wavelengths). Depending on the material, different spectral ranges can be covered and non-standard materials (like silicon, germanium, zinc selenide, indium phosphate) show excellent properties and results, especially in terms of roughness and WFE.

High-precision machining techniques (in particular diamond turning) make it possible to obtain unconventional gratings on curved surfaces or freeform gratings. The benefit of this could be a simplification of the optical design or an improvement of the capabilities (such as in the case of multi-blazed gratings). Moreover, such machines are suitable for working on large-sized substrates, matching the requirements of modern telescopes and instrumentation. In the case of spectropolarimeters, the use of liquid crystal gratings can provide interesting advantages, being able to control both the dispersion and the polarisation. A completely different approach is related to the use of photonic techniques, which exploit the dispersion induced in an optical waveguide system.

Conclusions and Remarks

This very focused workshop was characterised by a good mix of science and industry. There were more than 70 participants, coming mainly from Europe but also from the USA, Japan and Australia, interacting with representatives from 15 companies and research institutes that develop and manufacture dispersing elements and instrumentation.

The three days involved many animated discussions that extended beyond the workshop schedule. Indeed, there were several opportunities to network and discuss a range of related topics, including specific projects as well as new ideas.

One of the issues identified, was that numerous large gratings would be required over the next years to satisfy the requirements of the ELT instrumentation programmes as well as other existing and future spectroscopic facilities. Although astronomy is not a big industrial market, it is clear that there is room for many players as the requirements are challenging. The availability of many new technologies and capabilities will open up new alternatives, but in order to fully take advantage of all of the possibilities, interactions between instrument designers, industry and research institutes is crucial. This workshop was a successful first step in this direction.

Acknowledgements

We are grateful for the financial and logistical support that made this workshop possible. In particular, we would like to mention the financial support received from ESO, INAF (Italian National Institute of Astrophysics), and the Optical Infrared Coordination Network for Astronomy (OPTICON; an EU Horizon 2020 research and innovation programme under grant agreement No. 730890). We are also grateful to the staff of the INAF–Osservatorio Astronomico di Brera for their consistent support over the course of the workshop.

Links

[1] Workshop web page: http://www.brera.inaf.it/DispersingElements2017

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Report on the ESO–Radionet Workshop

Submillimetre Single-dish Data Reduction and Array Combination Techniques

held at ESO Headquarters, Garching, Germany, 15–16 March 2018

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Thomas Stanke[1]

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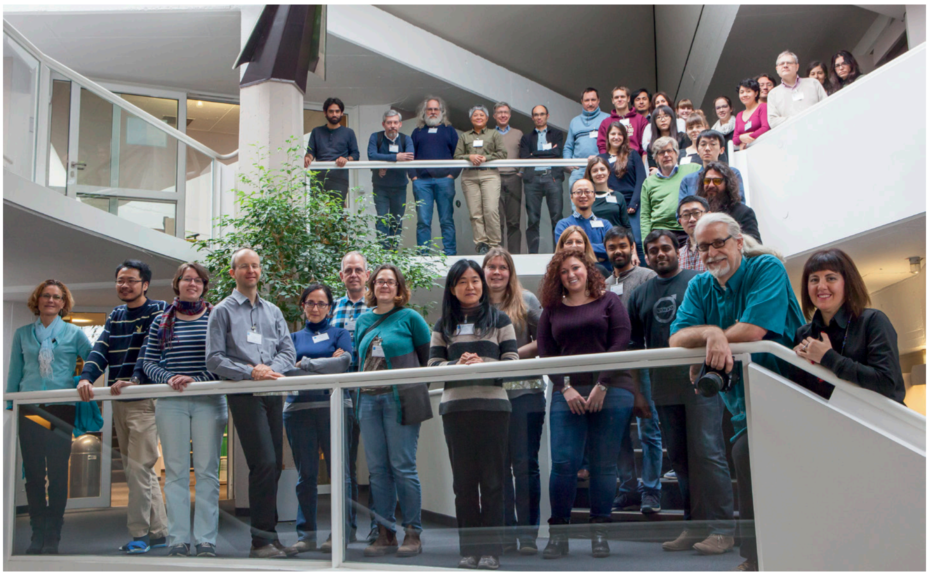
Single-dish submillimetre facilities provide an essential complement to the Atacama Large Millimeter/submillimeter Array (ALMA) interferometry data, but require a set of special observing techniques and data reduction software that are different from those applied to radio and millimetre facilities. As there has not been a dedicated workshop to inform the ESO user community about these specific aspects, we decided to organise such a workshop, with the generous financial support of Radionet which made the workshop possible.



ESO/L. Calçada

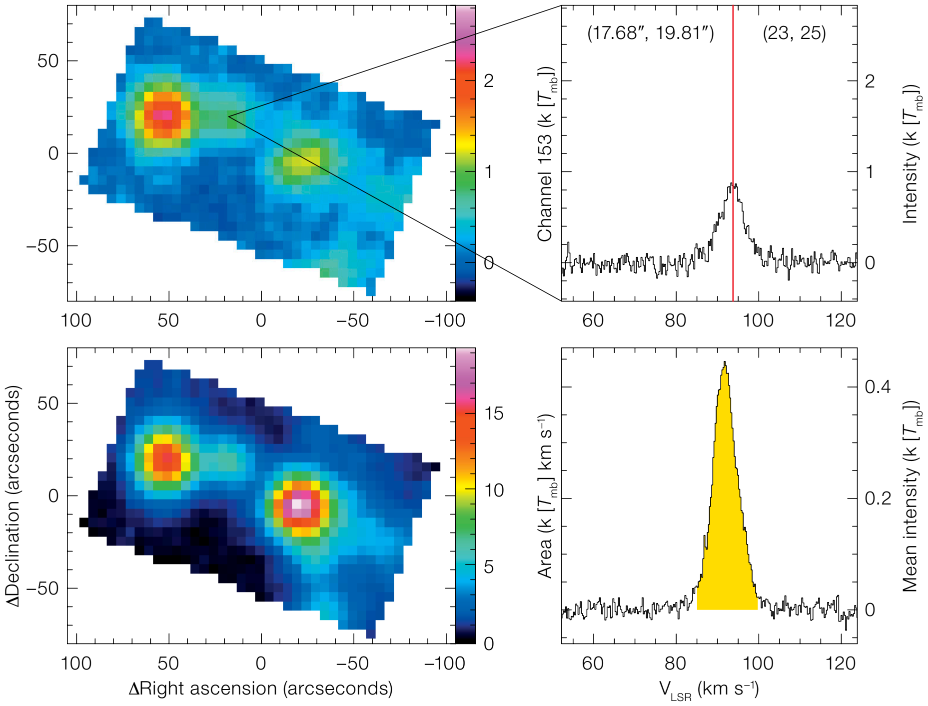
Figure 1. Workshop participants.

The workshop was attended by 42 participants (Figure 1), of whom 43% were women. The majority of the participants were PhD students or postdocs, likely reflecting those members of the wider community who are most actively working on this kind of data reduction[1].

The workshop began with a general overview by Thomas Stanke on the challenges of observing with single-dish telescopes at submillimetre wavelengths. In contrast to observing with interferometers, where the spatially extended sky signal is resolved, for single-dish telescopes, the sky dominates over the source signal by many orders of magnitude. Moreover, the sky signal varies significantly on timescales on the order of seconds. Most of the observing and data reduction techniques therefore need to concentrate on the removal of this bright sky emission. Additional challenges come from the atmospheric absorption bands and other instrumental effects. The subsequent lectures presented an overview of the ALMA and Atacama Pathfinder EXperiment (APEX) observing capabilities and observing strategies, followed by an introduction to the data reduction software used.

More than half of the time was reserved for (four) hands-on tutorial sessions. The first tutorial illustrated how to reduce ALMA total power data using the radio data processing package Common Astronomy Software Applications (CASA). Two additional tutorials showed how to reduce APEX heterodyne data using various alternative software packages: the Continuum and Line Analysis Single-dish Software (CLASS; see Figure 2); the Bolometer Array analysis software (BoA; Schuller, 2012); and the Interactive Data Language IDL pipeline using the map-making software Scanamorphos for ArTéMiS data (Roussel, 2013; Figure 3). All of these packages are freely available from either the Institut de Radioastronomie

Figure 2. Example from CLASS tutorial: an on-the-fly data cube of the giant molecular cloud W43 observed in CS with the Swedish Heterodyne Facility Instrument (SHFI) on APEX. T_{mb} is the main beam brightness temperature.



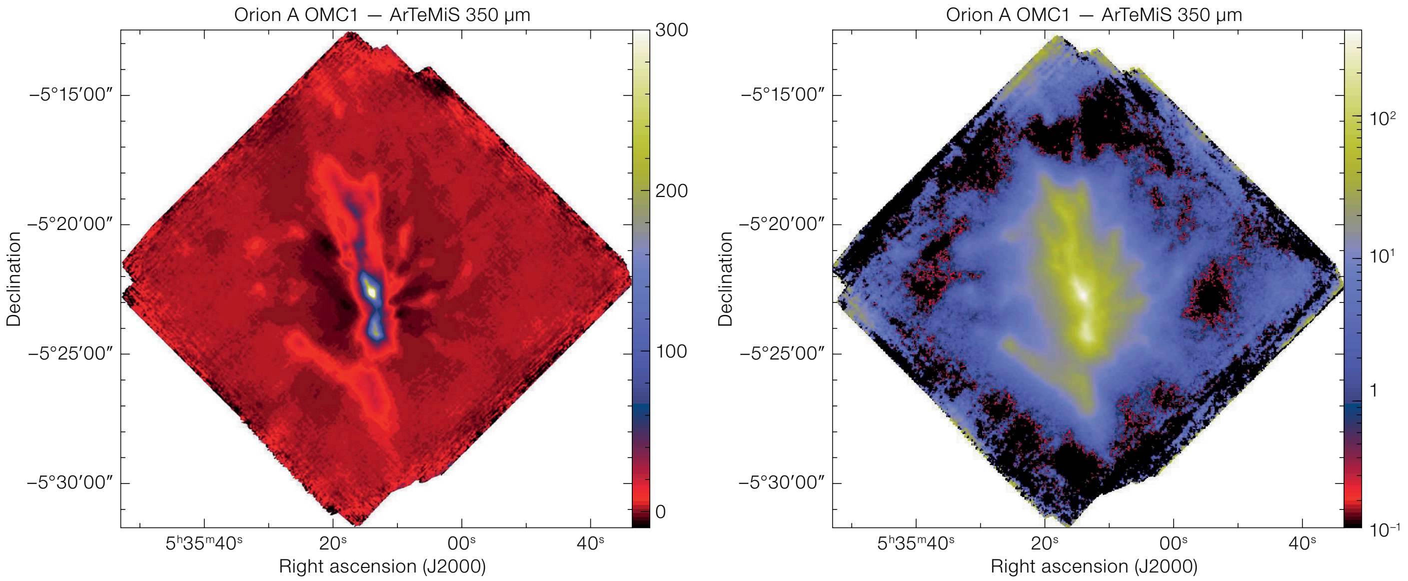


Figure 3. Example from the ArTéMiS data reduction tutorial. The image on the left shows the image after running through the basic ArTéMiS IDL pipeline. Note the negative bowls next to the bright emission, which are due to the over-subtraction of the sky signal. The image on the right shows the full reduction using the Scanamorphos pipeline, which uses the full redundancy of the data.

Millimétrique (IRAM) website for the Grenoble Image and Line Data Analysis Software (GILDAS[2]; Pety, 2005), or the APEX ArTéMiS pages[3].

One of the advantages of a single dish observation is that it can complement interferometric data by supplying information corresponding to short spacings that are filtered out by the interferometer, but that are necessary to recover the larger-scale emission. It is not uncommon to miss half of the flux in a more extended component when considering only interferometric data.

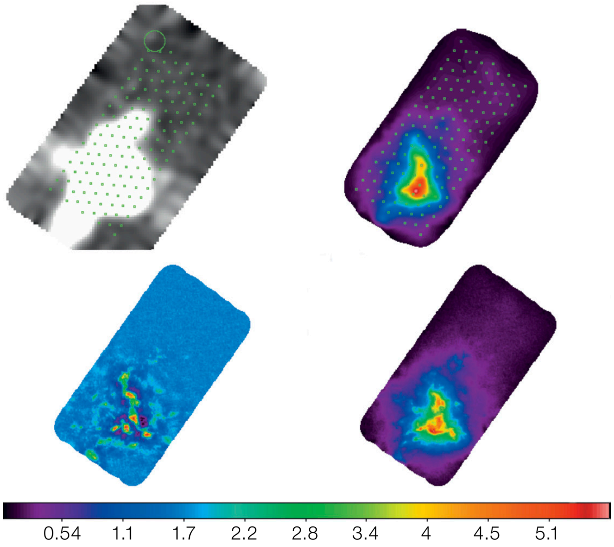


Figure 4. Top left: A channel from an ALMA total power observation of CO from a small region in the Small Magellanic Cloud. Overlayed on this greyscale are the pointing centres of the 12-metre array. For one pointing, the true extent of the 12-metre field of view is given as well with the larger green circle. Top right: The reconstructed total power map from the pseudo-visibilities generated from a virtual interferometer emulating the short spacings. Lower left: The pure interferometric map combining the 7- and 12-metre data. Lower right: Combining the total power visibilities with those of the 7- and 12-metre data recovers the large-scale flux as well as the fine scale structure. The size of each rectangle is ~ 5 × 3 arcminutes and the colour scale is in Jy/beam.

The majority of the second day in the workshop was spent on a number of techniques that have been developed and fine-tuned over the past 30 to 40 years, including a tutorial following the standard example of the M100 spiral galaxy using CASA, supplemented with two new techniques. The default method in CASA is called “feather”, but two new techniques were also highlighted: Short Spacing Corrections (SSC) — which combines two images — and the Total Power to Visibility tool (TP2VIS) — which replaces the single dish map with pseudo-visibilities that can be used in a standard joint deconvolution method to create images.

Talk slides, example scripts and example data are linked from the workshop web page[1], the workshop Zenodo repository[4], as well as via a github repository[5] that was updated throughout the workshop.

Acknowledgements

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References

Pety, J. 2005, SF2A-2005, ed. Casoli, F. et al., EdP-Sciences, Conference Series, 721
Roussel, H. 2013, PASP, 125, 1126
Schuller, F. 2012, SPIE, 8452, 84521T

Links

[1] Meeting web page: https://www.eso.org/sci/meetings/2018/SingleDish2018.html
[2] IRAM GILDAS website: https://www.iram.fr/IRAMFR/GILDAS/
[3] APEX ArTéMiS pages[3]: http://www.apex-telescope.org/instruments/pi/artemis/data_reduction/
[4] The workshop Zenodo web page: https://zenodo.org/communities/sd2018
[5] Github repository for the material used in the meeting: https://github.com/teuben/sd2018

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Report on the ESO Workshop

La Silla Paranal Users Workshop

held at ESO Headquarters, Garching, Germany, 12–14 March 2018

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Marina Rejkuba[1]

[1] ESO

In March, ESO organised the La Silla Paranal Users Workshop, providing current and future users of its observatories with an overview of the available instruments, as well as the most commonly used tools and processes at ESO, from proposal submission to data reduction and data archive. One full day of the event was dedicated to hands-on data reduction tutorials and one-to-one sessions between participants and ESO staff to work jointly on the issues brought up by the participants. The workshop attracted about 50 on-site participants as well as a dozen remote attendees, mostly from Australia.

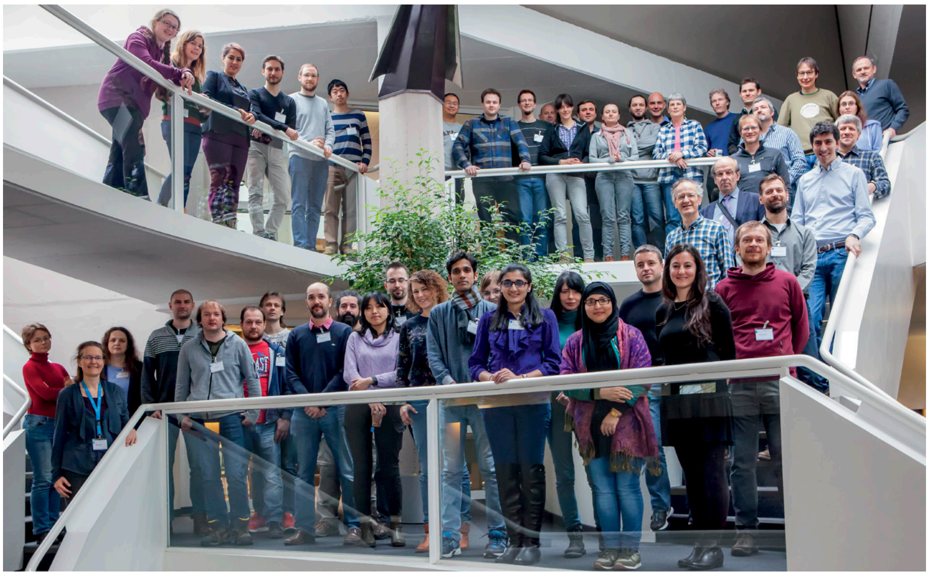

Figure 1. The workshop participants outside the ESO library.

ESO's ground-based observatories in Chile serve a very diverse astronomical community. The La Silla Paranal observatory offers astronomers the possibility of observing with a variety of telescopes, instruments and observing modes, including both Visitor Mode and Service Mode observations. Furthermore, the Observatory provides support to its users, monitors the quality of all observations and the status of its instruments, archives data, and for many instruments, delivers science grade pipelines and reduced data products. This level of support relies on complex machinery that, although efficient, may be daunting for members of ESO's user community. ESO therefore decided to host a three-day workshop, in order to present the various tools and services available and, at the same time, provide help with improving the technical aspects of their proposals, and with reducing data obtained with instruments at La Silla and Paranal.

Opening the workshop with a welcome address, Michael Sterzik, head of the Data Management and Operations division at ESO, reminded the audience that the La Silla Paranal Observatory uses a sophisticated and successful operational model, at the centre of which is the user community. This community is continuously growing, as there are about 100 new Principal Investigators (PIs) per semester submitting proposals to use ESO telescopes. As a result, there is a continued need for support and help for new users, especially those who are still in the early stages of their careers; this was one of the main aims of this workshop.

Moreover, ESO has recently signed a partnership with Australia and many Australian colleagues were very keen to learn about ESO. The original idea behind the workshop was to enable face-to-face interaction between users and ESO staff. However, given the strong interest from the new Australian community and considering the cost and time to travel to Garching from Australia, remote participation via Zoom was set up by our Australian colleagues to enable them to follow the various presentations and demonstrations in real-time. A few other colleagues, mostly from South America, also took advantage of this possibility. In total there were about 50 on-site participants, with a good gender balance (45% female), and strong participation from another recent ESO member state, Poland. Among the presenters, chairs and tutors, all from ESO (20 in total), the gender balance was not quite as good (33% female), but still representative of ESO staff.

The Very Large Telescope (VLT) Programme Scientist, Bruno Leibundgut, presented an overview of ESO and its observatories, stressing the great flexibility, scientific productivity and versatility of the La Silla Paranal Observatory. The Observatory instrumentation provides fields of view up to 1 degree, and a range of spatial resolutions with the smallest one less than 2 milliarcseconds, and a wide spectral coverage (from visible to infrared), which allows astronomers to probe the Universe in complementary ways. Bruno focused on some examples, such as the unique ESO exoplanet "machinery", comprising an unequalled suite of instruments: the High Accuracy Radial velocity Planet Searcher (HARPS); the Nasmyth Adaptive Optics System Near-Infrared Imager and Spectrograph (NACO); the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE); the VLT Interferometer (VLTI); the FOcal Reducer/low dispersion Spectrograph 2 (FORS2); and, soon, the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES+). He also emphasised the possibility of performing long-term observations, for example, of SN 1987A which has been observed over three decades at ESO observatories. Finally, he also outlined the various programmes, workshop series, and publications — such as the ESO Messenger — that allow ESO to maintain a link with its community.

Henri Boffin presented the impressive suite of instruments available at La Silla and Paranal and the science that they enable. Astronomers who wish to observe in the visible or infrared wavelength range are sure to find something that will suit their scientific goals. This will continue to improve, as ESO aims for the La Silla Paranal Observatory to maintain its world-leading position for at least another 10–15 years by means of continued instrument upgrades, as well as the addition of powerful new instruments (as Bruno Leibundgut had previously explained). This concerns not only the VLT but also the VLTI, the 3.5-metre New Technology Telescope (NTT), the ESO 3.6-metre telescope, and the 4-metre Visible and Infrared Survey Telescope for Astronomy (VISTA).

Among the impressive advances that will enhance the Observatory's capabilities in the coming years, new observing modes and future instruments were highlighted: the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO); GRAVITY's astrometric mode; the Multi-AperTure mid-Infrared Spectro-Scopic Experiment (MATISSE); the Multi Unit Spectroscopic Explorer (MUSE) AO Narrow Field Mode; CRIRES+; the Enhanced Resolution Imager and Spectrograph (ERIS); the Multi-Object Optical and Near-infrared Spectrograph for the VLT (MOONS); the Son Of X-Shooter (SOXS); and the Near Infra-Red Planet Searcher (NIRPS).

Most of these instruments can be used in Service (or queue) mode (SM) or in Visitor (classical) mode (VM). Francesca Primas and Michael Hilker highlighted the differences between these two observing modes, setting out their pros and cons. For example, VM allows real-time decisions and is best suited to challenging observations by experts. SM is most appropriate for demanding observing conditions — for example, transparency and seeing — as the observations are performed when the weather conditions fulfil the user's requirements. SM is also best suited to special observing strategies such as monitoring a particular target or field.

There is a clear educational aspect to observing in VM and, as Francesca pointed out, everyone should go at least once to the telescope to get acquainted with observing, and to become familiar with the sites and the people running operations. This helps to facilitate later interactions when observing in SM. SM observations provide a different educational opportunity, as they require the ability to structure one's observing strategy and clearly communicate it to the Observatory's staff who will be performing the observations following these instructions. The advantages of SM seem clear to the community. Michael showed that currently the fraction of VM requests is only around 15%, and more and more PIs are requesting SM.

The choice of observing mode, SM or VM, is made at the time of proposal preparation. Dimitri Gadotti and Nando Patat gave a talk about writing a successful proposal. They strongly suggested that everyone read the Call for Proposal (CfP) regularly, as this is the contract between ESO and the PIs. There is no miracle recipe for making a proposal successful, but Dimitri gave some guidelines and advice to follow when preparing and submitting a proposal — much of it based on common sense.

For those who are successful in getting their proposals approved and scheduled, Monika Petr-Gotzens explained how to make the most of the allocated observing time, i.e., how to define the right strategy and carefully plan the observations. A SM user should submit their observing material by the Phase 2 deadline, and check well in advance if any of the SM rules cannot be followed — in which case they would need to request a waiver. Too often users realise a waiver is needed the day before the Phase 2 deadline and start to panic. In SM, it is also crucial to monitor the progress of the scheduled observations and check the data immediately after they are acquired, so as to be able to react quickly in case there is any need for correction. In addition, Christian Hummel encouraged the audience to use the interferometric mode of the VLT as it is easier than most think.

John Pritchard presented an overview of the wealth of information available on the ESO website, including the possibility of seeing that the lasers are being used at Paranal while riding the Munich subway on the way to the workshop. The Science web pages contain invaluable material for preparing one's observations. There is even the possibility that people may be overwhelmed by the quantity of information available. Hence, the need for a clearer structure; the principal gateway for science users is the User Portal. However, it is still necessary to review the information contained in the ESO Science web pages, as it is not possible to link to everything relevant directly from the User Portal.

The ESO Science Archive, which was presented in detail by Martino Romaniello, is an important resource for astronomers. Martino explained the various flavours in which data can be downloaded, and also the archive services that allow users to easily find the science frames and the associated calibrations needed to reduce data. Around 2.6 million processed science files are present in the archive, ready to be analysed and published. However, Martino emphasised that the user may need to fully understand the dataset and triple-check the original files and data processing steps, especially in cases that involve unexpected findings. It is not always safe to blindly accept reduced data.

If the science data have not already been processed, one needs to use the data reduction process. Wolfram Freudling explained how this can be done, using ESO pipelines and also the ESO data organiser tools (EsoReflex and the command line ESO Recipe Execution tool EsoRex), which help to run the pipeline recipes in a structured way. Wolfram showed how EsoReflex organises the data, runs the recipes in order, displays final results and sometimes also intermediate products that facilitate the optimisation of parameters for a given reduction step. Once the optimal data reduction strategy is known, EsoRex offers another possibility to script and further automate data processing.

An important aspect of the workshop was to provide demonstrations and tutorials of the various tools and services available from ESO. Accordingly, Giacomo Beccari presented the new Phase 2 (p2) tool used to prepare observations in SM or VM. Jörg Retzlaff and Alberto Micol presented the archive services, illustrating the forthcoming new interface, and the possibility of making queries in a programmatic way. Lodovico Coccato gave a demonstration of how to reduce data with EsoReflex, as well as how to use the software Molecfit to remove atmospheric signatures from science spectra. Finally, John Pritchard showed how to modify EsoReflex workflows to tailor them to the user's aims.

One full day of the workshop was dedicated to hands-on sessions. In the first part, on Wednesday morning, three parallel tutorial sessions were held, during which participants were guided in using EsoReflex for three instruments, MUSE, the Ultraviolet and Visual Echelle Spectrograph (UVES) and X-shooter. These instruments were chosen as the majority of the participants expressed an interest in them when registering for the workshop. In each case, after a first step-by-step demonstration, the participants could choose to reduce a set of data provided by the organisers or to work on their own data. Two or three tutors were available for each session, helping and advising the participants in this endeavour. In the afternoon, participants were able to interact with ESO staff and discuss topics of their choice, including help with data reduction, help with proposal writing, finding information on ESO web pages, installing ESO software, help with observation preparations, and using the Science Archive either to access data or to return reduced data to the archive. At registration, participants were asked to indicate the area of the programme (proposal preparation, observing strategies and tools usage, data reduction) they would like to explore further. Participants were then split into small groups with overlapping interests, or had scheduled one-to-one sessions with the ESO staff member who was best placed to help with their specific topic.

At the end of the workshop, the organisers asked participants to provide feedback, and an extremely large number of people, more than 50% of the attendees, did so. The feedback was unanimously positive with all respondents saying they would recommend such a workshop to their colleagues. A few suggestions for similar future workshops were also received, with opinions differing, depending on the previous experience and knowledge of participants. It is our aim to repeat this workshop approximately every two years to promptly address questions from the continuous flow of new users of ESO facilities.

Acknowledgements

We would like to thank Véronique Ziegler for her help with the practical organisation, Stuart Ryder from the International Telescopes Support Office (ITSO) for setting up the remote participation via Zoom, and Sandor Horvath and the Information Technology (IT) staff for their help during the workshop. We most warmly thank all speakers and tutors for the great effort they made to provide clear and instructive talks or demonstrations and to efficiently help the participants in individual sessions.

Links

[1] All presentations as well as some of the video recordings are available on the workshop web page: https://www.eso.org/sci/meetings/2018/Users-Workshop/program.html

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Report on the

ESO–NEON Observing School at La Silla Observatory

held at ESO Vitacura, Santiago & La Silla Observatory in Chile, 18 February–2 March 2018

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Claudio Melo[1]
Giacomo Beccari[1]
Henri M. J. Boffin[1]
Valentin Ivanov[1]
Eleonora Sani[1]
Linda Schmidtobreick[1]
Michel Dennefeld[2]
Heidi Korhonen[3]

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During the two weeks between 19 February and 2 March 2018, the Office for Science at Vitacura and the La Silla Observatory were the hosts of the second ESO/NEON (Network of European Observatories in the North) La Silla Observing School. Thanks to the generous funding from ESO, the Optical Infrared Coordination Network for Astronomy (OPTICON), and the La Silla Observatory, a group of 20 students, consisting of mostly PhD but also some advanced MSc students, from different parts of the world, were guided by five ESO tutors. The students prepared and carried out complex observations, reduced and analysed the data, and finally presented the results to the ESO scientific community at Vitacura. In addition to learning about the observing techniques that were used during the school, the students also attended several lectures covering the current and future capabilities of the Atacama Large Millimeter/submillimeter Array (ALMA), the telescopes at Paranal, and the Extremely Large Telescope (ELT), as well as talks on what makes a good scientific presentation, time management, effective proposal writing, and career choices.

Over the course of three nights at La Silla, the students used the ESO Faint Object Spectrograph and Camera (EFOSC2) and

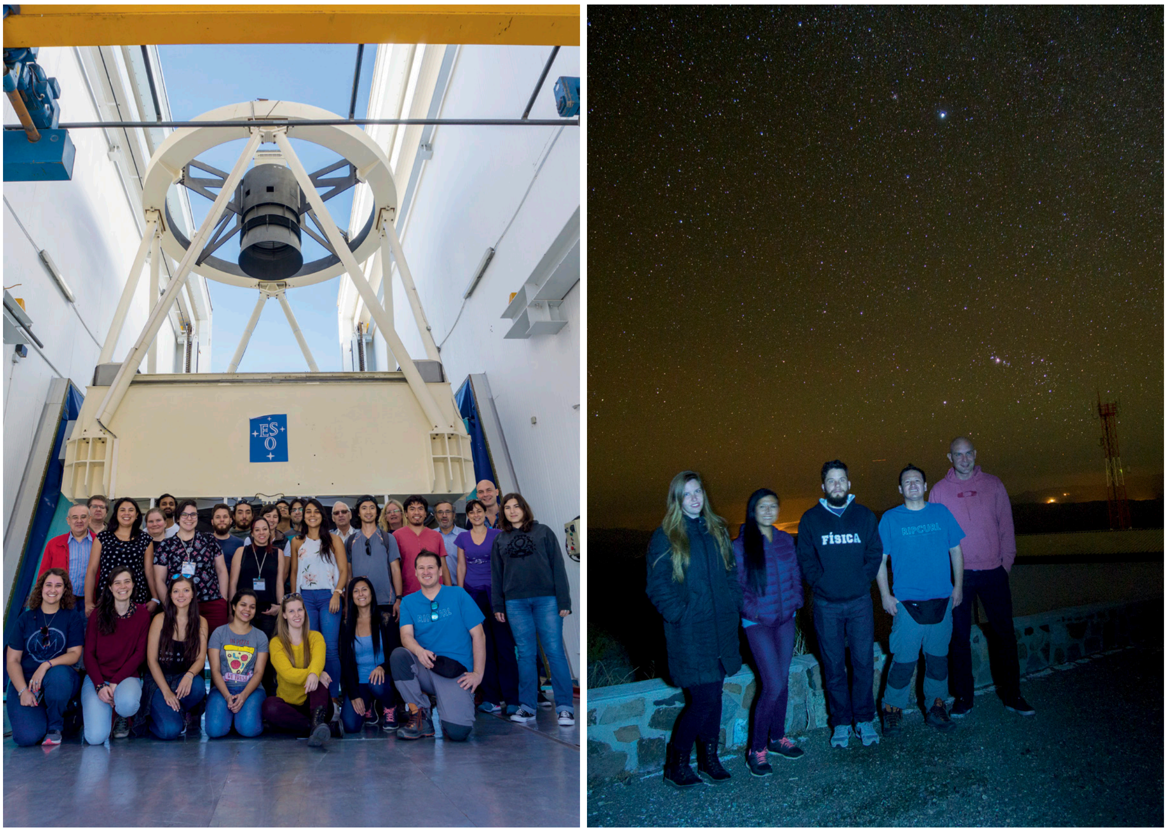

Figure 1. Left: The articipants, organisers, and tutors in front of the NTT telescope. Right: Giacomo Beccari´s group in front of their target.

the infrared spectrograph and imaging camera SOFI attached to the New Technology Telescope (NTT) as well as the Danish telescope, equipped with the Danish Faint Object Spectrograph and Camera (DFOSC). Divided into five groups, the students worked on a variety of astrophysical topics, supported by Heidi Korhonen at the Danish telescope, and by Monica Castillo and Ariel Sanchez at the NTT[1].

Giacomo Beccari guided a group studying Hα-excess sources in the Orion nebula and in Chamaeleon. In particular, the students acquired low-resolution spectra with EFOSC2 to study the equivalent width of the Hα emission line of 12 young T Tauri stars in Orion. Such emission in young stars is typically used to identify ongoing accretion from a protoplanetary disc. The measurements allowed the students to confirm the nature of the accretors in the observed objects spectroscopically. Similarly, DFOSC was used to perform broad-band *V*, *R*, *I* and narrow-band Hα imaging of young stars in Chamaeleon. The images, targeting a number of T Tauri stars with Hα emission studied by the Gaia–ESO

Figure 2. Students getting real-life experience at the consoles of the NTT (left), and the Danish telescope (right).

Figure 3. An interesting part of the school is the scheduling of the different programmes that compete for observing slots. Here the groups are trying to coordinate their observations in the La Silla School "War Room".

survey[2], were used to confirm their nature photometrically (i.e., whether or not they are accretors).

Henri Boffin led a group studying planetary nebulae, using both EFOSC2 and DFOSC to discover the binary stars that lurk at the centre of these majestic and colourful cosmic bubbles. The students were able to obtain the radial velocity curve and the *BVRI* photometric light curves of the binary star inside the planetary nebula DS1, and use these to determine the parameters of the binary. They also tried to uncover new binaries in some other planetary nebulae, providing useful upper limits as well as impressive colour images showing the intricate morphology of these objects. They finally derived the abundances in one of the planetary nebulae.

Valentin Ivanov's group followed the transit of two exoplanets: WASP-43b with SOFI, and WASP-19b with DFOSC. The data were processed and both transits were successfully detected. Light curves were fitted with publicly available transit analysis tools and various parameters of the planets were measured. The students also monitored the behaviour of the binary brown dwarf LUH 16AB over one night.

Eleonora Sani's group used SOFI to obtain the spectra of two quasars falling in the redshift range 2.5–3.5, i.e., at the peak of activity of cosmic active galactic nuclei. The rest-frame optical emission, redshifted into the *H*- and *K*-bands, was observed by means of low-resolution spectra. While the observation of the nearer quasar was affected by technical problems, the quality of the data for the $z \sim 3.5$ source allowed the complex profile of the emission lines to be decomposed into narrow and broad components. The students were therefore able to spot the signature of the broad-line region and to measure its size and the gas velocity dispersion, allowing them to make an estimate of the mass of the supermassive black hole of $2–3\ 10^8$ solar masses.

Linda Schmidtobreick's group worked on the spectral classification of variable star candidates; low-resolution optical spectra of the candidates were obtained with EFOSC2 and cross-correlated with catalogue spectra to obtain the spectral types of the objects. Together with externally provided light curves, the variability type of each object was discussed.

In addition to the above projects, low-resolution spectroscopy of three transient targets was obtained with EFOSC2. Two of these objects were classified as Type Ia supernova and the third one as a galactic nova. The students contributed to writing the corresponding astronomer's telegrams. These observations, together with a specific lecture about the "transient sky", aimed to draw the attention of the participants to this increasingly important topic, given the development of gravitational wave and neutrino detectors and the future arrival of the Large Synoptic Survey Telescope (LSST) in the southern hemisphere.

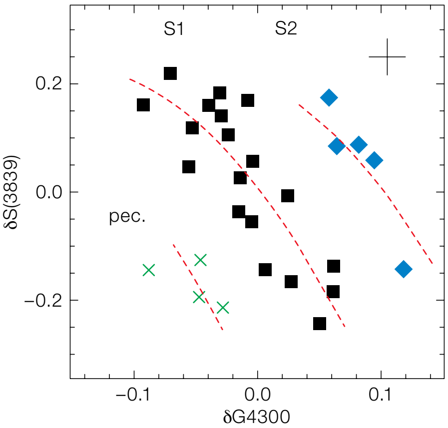

Figure 4. Distribution of CN and CH differential indices for Red-Giant Branch (RGB) stars of the globular cluster NGC 3201 determined by Bruno Dias's group in the 2016 school. Three groups are identified: the main, well-populated sequence 1 (S1); a second, less populated sequence 2 (S2); and a group of CN-weak/CH-weak peculiar stars (pec). Mean error bars are displayed in the top right corner. The dashed line was fitted to S1 stars and shifted by 1 magnitude in CH to match the S2 and pec stars (Dias et al., 2018).

An interesting aspect of these observing schools is that they can lead to publications, even though this is not a requirement. Bruno Dias was a tutor at the school in 2016, and led a group which carried out multi-object spectroscopy using EFOSC2 to study abundances in globular clusters. He recently published a paper with his students entitled "Galactic or extragalactic chemical tagging for NGC3201? Discovery of an anomalous CN-CH relation" (Dias et al., 2018). Bruno describes the work as follows:

"Globular clusters (GCs) are known to host stars with different light-element chemical abundances, such as C, N, O, Na, Al. In particular, the distributions of

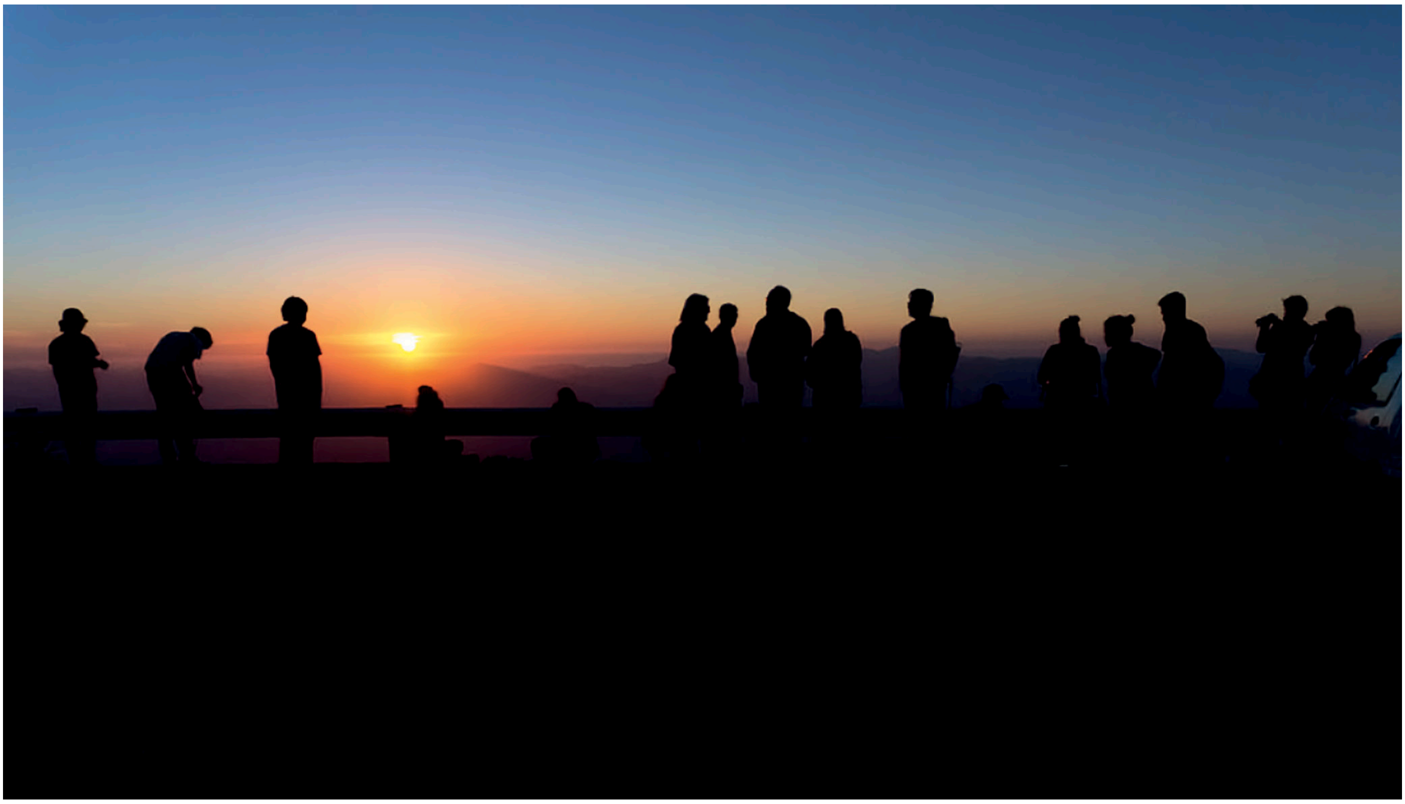

Figure 5. The students at the school, waiting for a green flash at the end of the first day.

C-N, Na-O are anti-correlated in typical GCs. A few anomalous clusters present multiple sequences of CN-CH anti-correlation, a proxy for C-N. These special GCs also share a few other odd characteristics; this is often interpreted as these GCs having originated in dwarf galaxies that were captured and destroyed by the Milky Way. Our results show that NGC 3201 presents multiple sequences of CN-CH, however it does not show other anomalous characteristics. We have therefore discovered the first GC that is neither completely typical nor completely anomalous, which means that the extragalactic origin scenario needs revision, and likely requires new stellar evolution models that can better explain how the CN-CH anti-correlation forms."

The spirit of the school was accurately summarised by an email from one of the students at the school, Gabriela Navarro from Universidad Andrés Bello (UNAB) in Santiago:

"I want to thank the organisers and tutors of the summer school. Both the talks and the research projects were tremendously interesting, and I am sure they will be very useful in the future. I also want to mention what was said among the students, that despite the level of stress generated, the school exceeded the expectations. This type of school is extremely useful for any astronomer regardless of the area chosen in the future. All the activities, from the talks to the visit to the observatory motivate us even more than we already are to continue doing research in our PhD."

It was intense and exhausting but we all feel that the process was well worth the effort. With this and the previous version of the school we have reached a total of 40 students who are now familiar with the way ESO does astronomy at the observatories in Chile. More importantly, we have been able to share our passion and, hopefully, helped the next generation of astronomers.

Acknowledgments

We would like to express our gratitude to ESO's Director General, the La Silla Paranal Observatory (LPO) Director and the Director for Science, without whose unconditional support this school would not have materialised. We would also like to thank the invited speakers at the school: Michele Cirasuolo, Alain Gilliote, Pascale Hibon, Yara Jaffe, Bruno Leibundgut, Adele Plunkett, Alain Smette and Frédéric Vogt. Hans Zinnecker was a special contributor to the school, first with a lecture on star formation, and second, contributing to lively discussions and debates about the different topics covered — heartfelt thanks to him! The logistical aspects of the school were handled by Paulina Jirón and María Eugenia Gomez, to whom we extend our deep gratitude.

References

Dias, B. et al. 2018, arXiv:1803.05124

Links

[1] ESO–NEON Observing School: https://www.eso.org/sci/meetings/2018/lasilla_school2018.html

[2] Gaia–ESO Survey: https://www.gaia-eso.eu/

DOI: 10.18727/0722-6691/5085

Fellows at ESO

Cyrielle Opitom

Cyrielle Opitom

I was born and grew up close to Liège in Belgium. As far as I can remember, I have always been interested in astronomy, space exploration and science in general, even if at the time I could not imagine that I would someday become an astronomer. I was simply curious to understand how things work, from inside the human body to the distant Universe. Later, in high school, I majored in mathematics and sciences, and I was lucky to have great maths and physics teachers who allowed me to cultivate and develop my interest in science.

After graduating from high school, I vacillated between biology and physics, but I finally decided to follow my first passion and to start a Bachelor in physics, with the intention of specialising in astronomy. The choice of university was easy since Liège University, which was just next door, was the only one in the French-speaking part of Belgium to offer a Masters in space sciences. Because I enjoy sharing my passion for space and astronomy, during my university years I had a summer job at the "Euro Space Center" in Belgium, developing activities aimed at kids and centred on the theme of space exploration. This was a great experience and encouraged me to continue to do outreach.

During my Master's degree, I took a class called "Small Bodies of the Solar System". At that time, I became fascinated by comets. In addition to being incredibly beautiful objects, they are types of fossils that allow us to study the history of the Solar System. There is a quote from David Levy, which I think describes comets particularly well: "Comets are like cats; they have tails and they do precisely what they want". This summarises how, after studying them for more than a century, comets remain mysterious objects and keep surprising us; and it is the reason I chose comets as the subject of my Master's thesis, during which I had the chance to work with the TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST) project, which consists of two 60-centimetre telescopes, one each in the northern and southern hemispheres. At the time I worked on it, only the southern telescope existed, which is hosted at the La Silla Observatory in Chile.

I really enjoyed this first encounter with research, especially with such fascinating objects as comets. I was lucky enough to get a grant, so could start a PhD in Liège, continuing with my Master's thesis work to study and compare the chemical composition of a large number of comets observed with the TRAPPIST telescope. Less than two weeks after starting my PhD, I flew to La Silla. This was a technical mission, and my first contact with a professional telescope was with a screwdriver in my hand. I immediately loved being at an observatory, especially working on a small telescope, where you can have direct contact with the instrument you are using. Being part of the TRAPPIST team gave me the opportunity to have an overview and get involved in all aspects of the facility, from technical aspects to scheduling to observing.

From the scientific point of view, I am thankful to my supervisor because I was given a lot a freedom to work on the project my own way as well as pursue new ideas. One of the most exciting parts of my thesis was my involvement in the ground-based support campaign of the ESA Rosetta mission. Sending a space mission to orbit a comet, and eventually landing on its surface was an incredible achievement, and it was a fabulous opportunity to follow the results and new developments of the mission while trying to link those to what we were observing from the ground. It is also in the framework of this ground-based campaign that I came to Paranal for the first time. This first experience at Paranal in addition to my previous ones at La Silla (and the incomparable beauty of Chile) played an important role in my decision to apply for an ESO fellowship after the end of my thesis.

This is how I ended up in Chile, living abroad for the first time. I have never regretted my decision to come to ESO Chile and highly appreciate the stimulating multi-disciplinary environment and the opportunity to learn about very different scientific topics. I also enjoy the freedom that I have to pursue my own research, and to try to expand our understanding of the composition of small bodies of the Solar System.

ESO offers a lot of opportunities that I would not have elsewhere, especially as a young scientist; I get to mentor students, define my own projects, take up responsibilities, and organise conferences. Thanks to my duties in Paranal, I have learned a lot and gained familiarity with new instruments and new techniques. Being assigned to the HAWK-I infrared imager, I have also participated in the commissioning of its adaptive optics module, working with a really great team. The teamwork is something I particularly appreciate about Paranal. In the future, I hope I can continue to do research and keep observing regularly, as I love being in an astronomical observatory. In any case, I feel lucky to have a family who always encouraged me to pursue a career in astronomy. It made it so much easier to get here.

Chris Harrison

What a luxury it is to be a professional astronomer. I actually get paid to use huge telescopes to study supermassive black holes destroying galaxies. Yet, perhaps surprisingly, my journey to an ESO Fellowship has not been a clear predefined path towards astronomy after some inspirational events during my childhood. Instead, my route to becoming an ESO Fellow has been filled with indecisiveness, difficult decisions and self-doubt, but also, most importantly, influential and supportive people.

Beyond wanting to go to university in my home country of the UK, at the age of 17, I really did not know what I wanted to do after school. I ordered around 40 university prospectuses and spent hours flicking through the pages looking for inspiration. After a systematic approach to whittle down the options (involving an Excel spreadsheet), I was left with either astrophysics or digital multimedia design. It was almost a flip-of-a-coin decision that resulted in my opting to enroll on an integrated (four-year) Master's Degree in astrophysics at the University of Edinburgh.

After a couple of months of my degree I had my first experience of what is now widely known as "imposter syndrome" and nearly dropped out, believing that I didn't have what it takes. Thanks to support from my parents and a new friend (who ended up being the best man at my wedding), I decided to try a second semester. I eventually found my feet and started to feel a real passion for astronomy. This was especially true for the third-year research projects, particularly when I was using a small telescope on the roof to make colour-magnitude diagrams of stellar clusters under the supervision of Rob Ivison. During this time, I also found great joy in volunteering to do outreach at the Visitor Centre at the Royal Observatory.

Eventually I came to the conclusion that my skills would be best used by becoming a physics teacher. I decided to not take a full Master's qualification, but to leave after my third year with a Bachelor's degree and take the "spare" year to go travelling with my girlfriend (who is now my wife). However, on getting wind of this, Rob Ivison took me into his office and said, "you should consider a PhD". Consequently, I thought it might be sensible to make some initial enquiries about doing a PhD when I returned from my travels. This is when I first met Dave Alexander with his infectious enthusiasm for anything related to supermassive black holes.

Chris Harrison

Four months of backpacking in Southeast Asia and five months of bush camping in Western Africa gave me a considerable amount of time to reflect upon what I wanted from life. I concluded that it might be quite fun to undertake a PhD. I was lucky enough that Dave Alexander was able to take me on as his student at Durham University. He set me off on reducing integral field spectroscopy (IFS) data from the Near-Infrared Integral Field Spectrometer (NIFS). These data were of distant star-forming galaxies that host rapidly accreting black holes, and the goal was to search for evidence of gas being expelled from the galaxies. The project was certainly exciting, and I was delighted to have a set of data that nobody else was working on. Despite this, I briefly felt again that I did not have what it takes to be an astronomer and the other students were much more intelligent and better researchers. However, thanks to supportive people around me, I managed to continue.

My PhD evolved into using Herschel Space Observatory data to study star formation rates in distant active galaxies. Then I started working on data that I had been awarded as Principal Investigator and began to take charge of my own research. During my PhD I also took advantage of many exciting opportunities to do outreach, for example, delivering planetarium shows, giving public talks, and designing exhibitions for science festivals. For my first postdoctoral position, I stayed on at Durham, taking control of large ESO projects involving the *K*-band Multi-Object Spectrograph (KMOS) to study the internal gas kinematics and dynamics on hundreds of distant galaxies; some of Durham's Guaranteed Time on KMOS.

With a wife, a one-year old daughter and a son on the way, it was difficult to decide to move the whole family to Germany in order to take up the ESO Fellowship. However, the pull of the fantastic opportunities that working at ESO would bring, and of living in Munich, were too great to resist. It is such a privilege to be working at the Headquarters, alongside such a broad range of people. I now am working on a range of datasets, from programmes I am leading involving radio interferometry (eMERLIN; VLA; ALMA), more IFS data (ESO/VIMOS; ESO/SINFONI) and X-ray data (Chandra); these are mostly driven by the goal to establish the connection between supermassive black holes and their host galaxies. I am also lucky enough to have two excellent students working alongside me on these projects.

I am elated to be working alongside the Supernova coordinator Tania Johnston on the ESO Supernova Planetarium & Visitor Centre for 25% of my time (my "ESO project"). I feel honoured to have been part of developing the educational workshops and planetarium shows, and I am now getting to see them in action, since we opened in April of this year. At ESO, I also have the role of being one of the fellow representatives, which gives me the opportunity to improve and refine the Fellowship programme for the other ESO Fellows. Indeed, this has lately become a strong ambition — to ensure that astronomy can be a safe, supportive and enjoyable career for everyone. After all, it is a luxury to be able to do this job, and we should all be having a fun time doing it.

Miguel Querejeta

Miguel Querejeta

I was six years old when I first looked through a telescope. It was in a small town called Ezcaray, in the Spanish wine-producing region of La Rioja. I used to spend long summer periods there with my family and those dark night skies always fascinated me; I distinctly remember the feeling of the chilly breeze on a deck chair on the roof terrace, watching shooting stars for hours on end. In such a setting, it seems natural to wonder about the physical nature of those shiny objects — and here I am, more than 20 years later working as a professional astronomer!

However, the fact that I felt such an early fascination for astronomy did not mean that I always wanted to pursue studies in that direction. As a teenager, I seriously considered the option of studying mathematics, neurobiology, classics, and even history of art, which drove my parents a bit crazy. Despite my whims, the support from my parents was always admirable, and they encouraged me to follow my passion for astrophysics. This eventually took me to Madrid, where I studied Physics with Astronomy at the Universidad Complutense.

From 2011–2012, I was fortunate enough to spend a year abroad at the University of Nottingham through the Erasmus scheme, which is a European community action scheme to encourage the mobility of university students. I was guided by a brilliant tutor, Alfonso Aragón-Salamanca, and I had some excellent lecturers there, such as Mike Merrifield, Chris Conselice, and Omar Almaini. The atmosphere of the Nottingham Astronomy Group was very enthusiastic, and I was able to undertake a year-long research project under the supervision of Loretta Dunne: using data from the Herschel Space Observatory to study dusty early-type galaxies — which I very much enjoyed.

That initial research experience at Nottingham motivated me to look further for possible internships, and I obtained a studentship to spend a whole summer at the Intituto de Astrofísica de Canarias, in Tenerife. There, I analysed dynamical resonances in galaxies with John Beckman and Joan Font. I was stunned by the telescopes in La Palma, and it was one of the most memorable summers of my life.

At that point, I was fully convinced that I wanted to embark on a PhD in astrophysics by the end of my undergraduate studies, and my colleagues from Tenerife informed me about an interesting opportunity: a Marie Curie Initial Training Network called Detailed Anatomy of GALaxies (DAGAL). This included several positions across Europe in the field of nearby galaxies, and I opted for the project in Heidelberg: a decision that I did not regret! I conducted my PhD at the Max Planck Institute for Astronomy, supervised by Eva Schinnerer and working closely with Sharon Meidt, to whom I owe a lot. My PhD area was quite broad and included investigating how stellar mass is distributed in galaxies, molecular gas flows, and nuclear activity, while spanning a wide range of wavelengths and techniques.

Obtaining an ESO Fellowship straight after the PhD was like a dream come true, as it was at the very top of my list of preferences. One of the most attractive aspects of working at ESO is interacting with such a wide range of people; the atmosphere is extremely friendly, and everyone is very approachable and willing to help. As an example of the cooperation among ESO Fellows, I would like to highlight a workshop that we recently organised on galaxy interactions and mergers. The entire journey from the initial seed of a crazy idea to the final event was the result of the fruitful collaboration of five ESO Fellows. The conference took place in Sexten (Italy) in March 2018, and it attracted experts from all over the world; the result was a most enjoyable and productive workshop, leading to a healthy exchange of ideas and triggering new projects and collaborations.

My main research focus at ESO is trying to understand the factors that regulate the conversion of gas into stars in nearby galaxies; for that goal, I rely on observations from interferometers such as the VLA, NOEMA, and ALMA. This research is largely pursued in the context of international collaborations, and working with such a wide range of people makes it particularly attractive to me. In addition, my functional duties include developing outreach material for the ESO Supernova Planetarium and Visitor Centre, and I am one of the visiting observers for the APEX telescope in Chile.

Ironically, very soon after I started in Garching, I was awarded a permanent position at the Observatorio Astronómico Nacional in Madrid, where I will move in a few months. I tried my luck with the application encouraged by colleagues from Madrid, honestly thinking that my chances were vanishingly small. But life is full of surprises, and if there is one thing that I have learned over the years, it is that one should always try, no matter how hard or unlikely something may seem! In retrospect, I can hardly believe the chain of coincidences that has brought me to where I am. I feel most privileged to work in a field like astronomy, which is so exciting and full of inspirational people.

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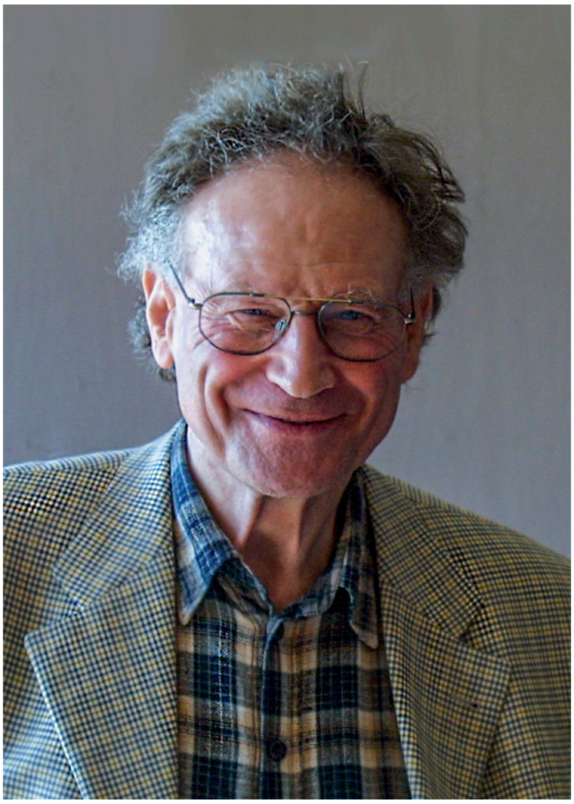
Raymond Wilson, 1928–2018

Martin Cullum[1]

[1] ESO

Ray Wilson, who worked at ESO for 21 years, died on 16 March 2018. He made an indelible impression on ESO, as well as on the design of modern large telescopes worldwide.



Ray was born in Sutton Coldfield in the UK, the youngest of four children. At school he excelled in Latin and history, but made much less impact in mathematics. Nevertheless, he had an early interest in astronomical optics and even built himself a telescope as a teenager. It was his mother who, influenced by a family friend, later persuaded him to study physics rather than the humanities. She thought — probably rightly — that it would offer better employment possibilities. Ray took his first degree in physics at Birmingham University and then went on to Imperial College in London as a postgraduate. It was here that he discovered his love of optics and optical design and his PhD thesis, presented in 1953, was entitled “The Production of Aspheric Surfaces”.

After leaving Imperial, Ray joined the traditional British optical firm Ross and Company doing, as he said, what he liked doing best — designing optics. Unfortunately, this was not to last long. In the post-war decades the European optics industry was in flux. Many traditional commercial optics firms in England and France were going bankrupt in the face of German, and later, Japanese competition. Ross went bankrupt and Ray moved to the National Physical Laboratory (NPL) in Teddington in South West London in 1955. Earlier, the NPL had been very strong in optical design and aberration theory, but a new manager decided to concentrate on practical optics research which did not appeal to Ray. So, after three years at the NPL, he decided to look for employment in the thriving German optical industry. Through a former German colleague at Ross, Ray was offered a position in a small optics firm in Trier, called Karl Foitzik. This firm also went bankrupt within 10 months of Ray’s joining and his next job was with Carl Zeiss. In 1959, there was no position free in optical design at Zeiss, and he was offered a position in the photographic laboratory, which was responsible for testing and quality control. This was partly theoretical, which suited him, and partly practical, which did not, but he was happy to be working for such a prestigious firm.

In September 1960, Ray received an offer to return to Imperial College London as an assistant lecturer to conduct theoretical research on the application of computers to optical design. He stayed there until the summer of 1963, and then returned once again to Carl Zeiss in Oberkochen, who had offered him his “dream position” in the optical design department for astronomical and analytical instruments.

In the early 60s there was a small epidemic of poliomyelitis in the region of Baden-Württemberg where Ray lived, and he contracted this disease shortly after returning to Zeiss. He was away from work for 10 months convalescing and, although he recovered, he was left with a slight disability.

After five years at Carl Zeiss, Ray was made head of department and his career seemed settled and secure for life, but clouds were forming on the horizon. In 1970, German industry was hit by a massive financial crisis. Carl Zeiss was also seriously affected by this recession and many of the staff in Ray’s department were made redundant, through no fault of their own. While at Zeiss, Ray had already had contact with ESO through preliminary design contracts for the ESO 3.6-metre telescope. The unpleasant situation at Zeiss motivated him to look elsewhere and, in 1972, he was offered a position as head of the optics group in ESO’s Telescope Project Division at CERN in Geneva.

Even several years before Ray moved to ESO, ideas about the active control of telescope optics, now commonly known as Active Optics, had been brewing in his mind. His collaboration with Gerhard Schwesinger, who had developed an analytical model of the aberrations introduced by support errors of primary mirrors, furthered these ideas. However, two problems remained: how to measure the support errors and how to correct them.

The ESO 3.6-metre telescope was equipped with a so-called Hartmann screen. This was a metal plate, the same diameter as the primary mirror, with an array of high precision holes bored in it. This was placed just in front of the primary mirror and a series of extra-focal photographic images were taken at different telescope positions. After scanning and analysing these images, the optical aberrations could be estimated. Not only was this a cumbersome and risky procedure, but the possibilities of correction with the 3.6-metre telescope were limited by the very heavy and stiff primary mirror. Nevertheless, Ray's position at ESO allowed him to develop the idea of Active Optics for future telescopes, and eventually to provide solutions to these problems. Even in the late 70s, ESO, along with other major observatories, was already thinking about the next generation of giant telescopes.

From 1979–1980, Ray spent a year at La Silla working with the optical group to gain experience in the operation and maintenance of large telescopes. This convinced him even more that future telescopes should have thin flexible primary mirrors with an active control system that would be able to correct optical misalignment and compensate for gravitational and thermal mirror distortions. About this time, Ray visited a former student colleague from Imperial College, Roland Shack, who was now professor at the Optical Sciences Center in Tucson, Arizona. Shack had invented a compact and efficient optical test device that was based on the classical Hartmann test, but could be mounted directly in the telescope focal plane. Ray immediately saw the importance of this device for future telescopes and set about having one built at ESO. The device became known as the Shack–Hartmann wavefront sensor. When this was later coupled to a CCD detector for image readout, ESO had a practical device to measure telescope aberrations in real time. However, to actively correct aberrations would require a telescope with a much thinner primary mirror than classical large telescopes like the ESO 3.6-metre. But to propose the construction of a very large telescope based on untested technology would have been a giant leap of faith that would hardly be accepted by the ESO Council. Fortunately, Switzerland and Italy provided the solution. In 1982, both countries became ESO Member States and with their entry fees ESO decided to build another telescope to ease the load on the already oversubscribed 3.6-metre telescope. At the same time, this provided the Organisation with the opportunity to gain experience with innovative telescope technologies. Ray Wilson, by now head of the ESO Telescope Group, saw the opportunity to design a modern 3.5-metre alt-azimuth telescope that eliminated some of the recognised problems with the 3.6-metre.

Ray persuaded the then Director General, Lodewijk Woltjer, to build the new telescope with an actively controlled thin primary mirror. Woltjer agreed under the condition that the New Technology Telescope (NTT), as it would be known, must have a performance no worse than the 3.6-metre telescope even if the active control did not work as planned. Another innovation of the NTT was the free airflow enclosure design. This concept had been pioneered at the Multiple Mirror Telescope on Mt. Hopkins in Arizona and differed markedly from that of classical telescope domes, which had small apertures to "protect" the telescope from the outside environment. Having a relatively thin primary mirror and effective air flow through the enclosure allowed the telescope — and in particular the primary mirror — to be in thermal equilibrium with the ambient environment, instead of being isolated from it. Ray recognised the importance of this development and it became an important feature of the NTT concept.

The First Light of the NTT in March 1989 took place under excellent seeing conditions, allowing the NTT to demonstrate its performance to the full. This it certainly did, producing probably the best images ever obtained from a ground-based telescope at that time, and three times better than had ever been obtained with ESO's 3.6-metre telescope. And all of this was at a third of the cost of the 3.6-metre telescope! Almost overnight, ESO's reputation as an innovative and leading organisation for astronomical research was established. The overwhelming success of the NTT, founded to a very large extent on the insight and perseverance of Ray Wilson, changed the way future large telescopes would be designed and fully validated the decision of the ESO Council to go ahead with the construction of the Very Large Telescope (VLT).

Ray was a reluctant manager. He never strived for power or influence and, although justly proud of his achievements, was always self-deprecating. But with his abundant enthusiasm he very effectively led and inspired the dedicated group of physicists, engineers and technicians who developed Active Optics technology at ESO, implementing it on the NTT and later — in a more extreme form — on the VLT. He was happy to give credit to his colleagues and was always willing to listen and explain. He could talk as naturally to the Director General as he could to the ESO janitor and was thus greatly respected within the Organisation on a personal level as well as for his technical expertise.

During his final three years at ESO, and after he retired in 1993, Ray worked on a two-volume monograph "Reflecting Telescope Optics". These two volumes, published in 1996 and 1999 respectively, remain classical works on the development and design of optical telescopes that represent a lasting epitaph to Ray's lifetime achievements.

In the latter part of his career, Ray was awarded numerous prizes and honours for his contributions to the advancement of telescope technology. These include the Medal of Geneva University in 1993, the Karl Schwarzschild Medal of the German Astronomical Society in 2003, the Chevalier of the French Légion d'Honneur in 2004, the Prix Lallemand of the French Academy of Sciences in 2008, the Kavli Prize of the Norwegian Academy of Science and Letters (together with Roger Angel and Jerry Nelson), as well as the Tycho Brahe Prize of the European Astronomical Society in 2010.

He leaves his wife, Anne, and two sons from his first marriage, Geoffrey and Peter.

Personnel Movements

Arrivals (1 April–30 June 2018)

Europe

Kravchenko, Kateryna (UA)	Student
Sagatowski, Jakob (SE)	Software Engineer

Chile

Gallilee, Mark (UK)	Mechanical Technical Lead
Mejia-Restrepo, Julian (CO)	Fellow
Sánchez Sáez, Paula (CL)	Student
Wibowo, Ridlo (ID)	Student

Departures (1 April–30 June 2018)

Europe

Guillard, Nicolas (FR)	Student
Man, Wing Shan (CN/HK)	Fellow
Peest, Peter Christian (DE)	Student
Scholtz, Jan (CZ)	Student

Chile

Faez, Robinson (CL)	Telescope Instruments Operator

ESO

European Organisation
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Research in the
Southern Hemisphere

Annual Report 2017

The ESO Annual Report 2017 is available online now at eso.org/public/announcements/ann18041/.

ESO, the European Southern Observatory, is the foremost intergovernmental astronomy organisation in Europe. It is supported by 15 countries: Austria, Belgium, the Czech Republic, Denmark, France, Finland, Germany, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland and the United Kingdom. ESO's programme is focused on the design, construction and operation of powerful ground-based observing facilities. ESO operates three observatories in Chile: at La Silla, at Paranal, site of the Very Large Telescope, and at Llano de Chajnantor. ESO is the European partner in the Atacama Large Millimeter/sub-millimeter Array (ALMA). Currently ESO is engaged in the construction of the Extremely Large Telescope.

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Front cover: *JHK* colour-composite image of the central region of The massive star forming region RCW 38 from HAWK-I using the ground-layer adaptive optics module, enabling a study of the detailed influence of photoionisation from massive stars on star formation across a wide range of stellar masses down to brown dwarfs. Credit: ESO/Muzic et al.