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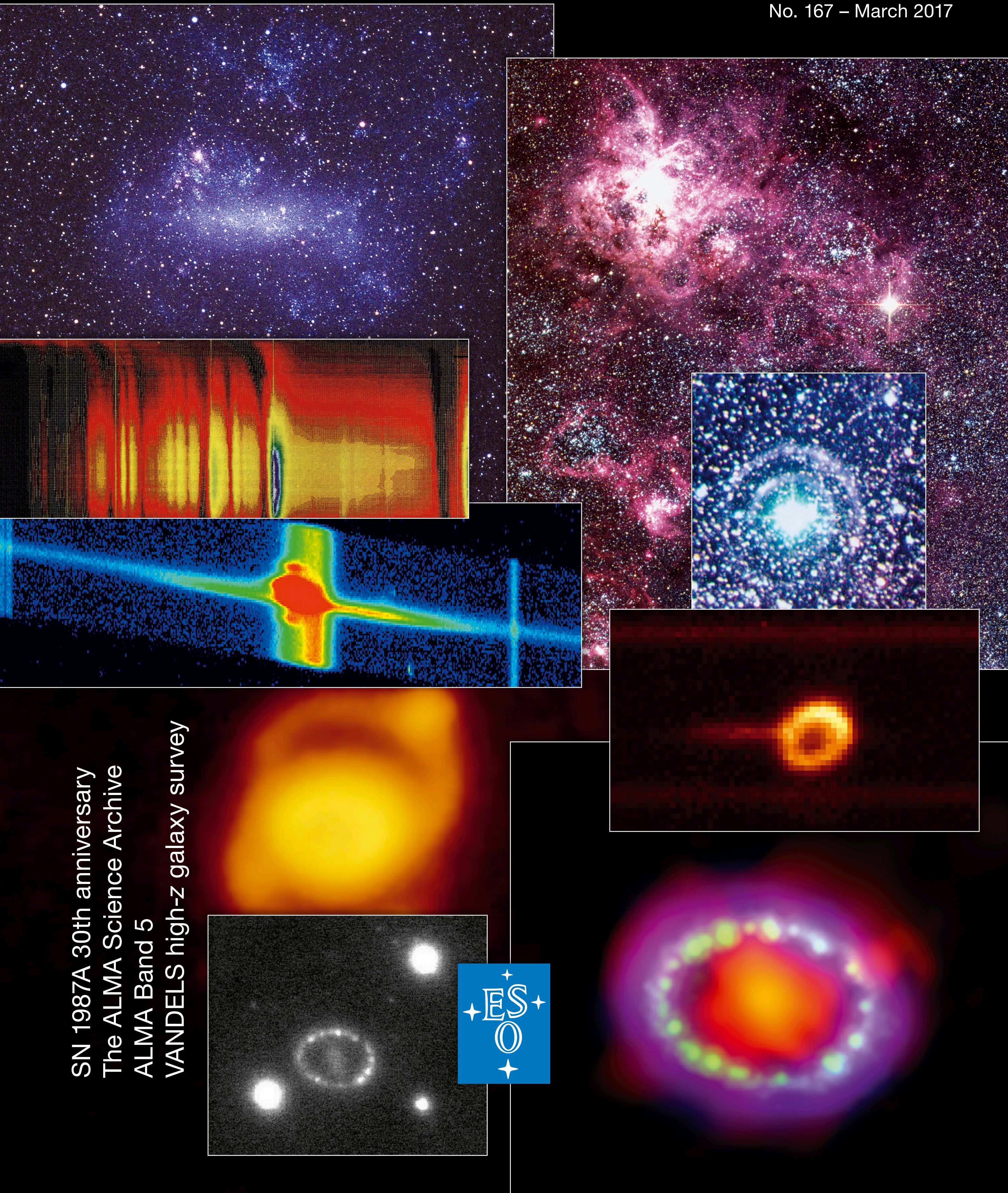

SN 1987A 30th anniversary
The ALMA Science Archive
ALMA Band 5
VANDELS high-z galaxy survey

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The ALMA Science Archive

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Science archives help to maximise the scientific return of astronomical facilities. After placing science archives into a slightly larger context, we describe the current status and capabilities of the ALMA Science Archive. We present the design principles and technology employed for three main contexts: query; result set display; and data download. A summary of the ALMA data flow is also presented as are access statistics to date.

Introduction

The overall success of an astronomical facility is measured by the quality and quantity of science produced by its community. By helping the principal investigators (PIs) and archival researchers of the facility to easily discover, explore and download the data they need, a science archive helps to maximise the scientific return and thus to increase the success of the facility. In addition to the delivery of data to PIs, provision of data-persistence for independent verification of scientific results and duplication checking in the proposal process, one of the main purposes of a science archive is indeed to enable independent research.

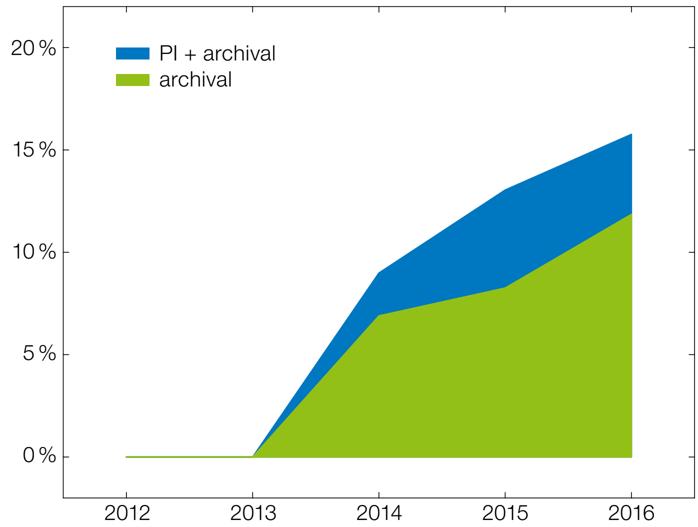

Figure 1. Fraction of ALMA publications that make use of either only archival ALMA data (green) or both ALMA PI and archival data at the same time (blue). 2013 was the first year when ALMA PI data became public and thus the first archival publications appear in 2014.

For only a very small fraction (of the order 1–3 %) of the total yearly operational cost of a facility, substantial additional scientific progress can be obtained through public provision of a science archive. This is, for example, true in the case of the Hubble Space Telescope (HST), where publications making use of archival data have by now outnumbered the publications of PI observations by the proposing teams. Romaniello et al. (2016) also report the growth of an ESO archive community, where almost 30 % of users downloading data from the Science Archive Facility (SAF) have never been PI or co-investigator of an ESO proposal. For the still very young Atacama Large Millimeter/submillimeter Array (ALMA) facility and its ALMA Science Archive[1], we can report a rapidly increasing fraction of publications making use of archival data (Figure 1), already reaching 16 % (or 27 % including publications from Science Verification data) in 2016 (see also Stoehr et al., 2015).

The requirement that data be well described and easy to discover through science archives can be expected to grow rapidly in the future, as the amount of data increases exponentially. For example, we estimate that the fully operational Square Kilometre Array (SKA) will deliver around 200 TB per year of science images for every active astronomer in the world at that time. As astronomy will inevitably transform into a science where the largest fraction of observed pixels will never be looked at by a human, machine-aided analysis will inevitably increase in importance. This approach includes scientific pre-analysis (for example, the ALMA Data MIning Toolkit, ADMIT: Teuben et al., 2015), remote visualisation (for example, the Cube Analysis and Rendering Tool for Astronomy, CARTA: Rosolowsky et al., 2015) and remote analysis (code-to-data), as well as analysis based on machine learning. In particular, deep learning is currently witnessing an epochal change and dramatic new possibilities can be expected over the next few years. Successful approaches, like automatic caption generation for images[2] and human-quality astronomical object classification (Dieleman et al., 2015), give an indication of the future prospects in this area. A powerful well-characterised science archive is the basis of such data-mining.

Depending on the nature of the project and its goals, and notwithstanding the remark about the small operational costs of archives, the fraction of the total cost that astronomical facilities spend on data management is expected to slowly increase. An extreme showcase of this evolution, admittedly in a different context, is the Large Synoptic Survey Telescope (LSST), where 52 % of the total survey cost of $1.25 billion is expected to be spent on data management[3].

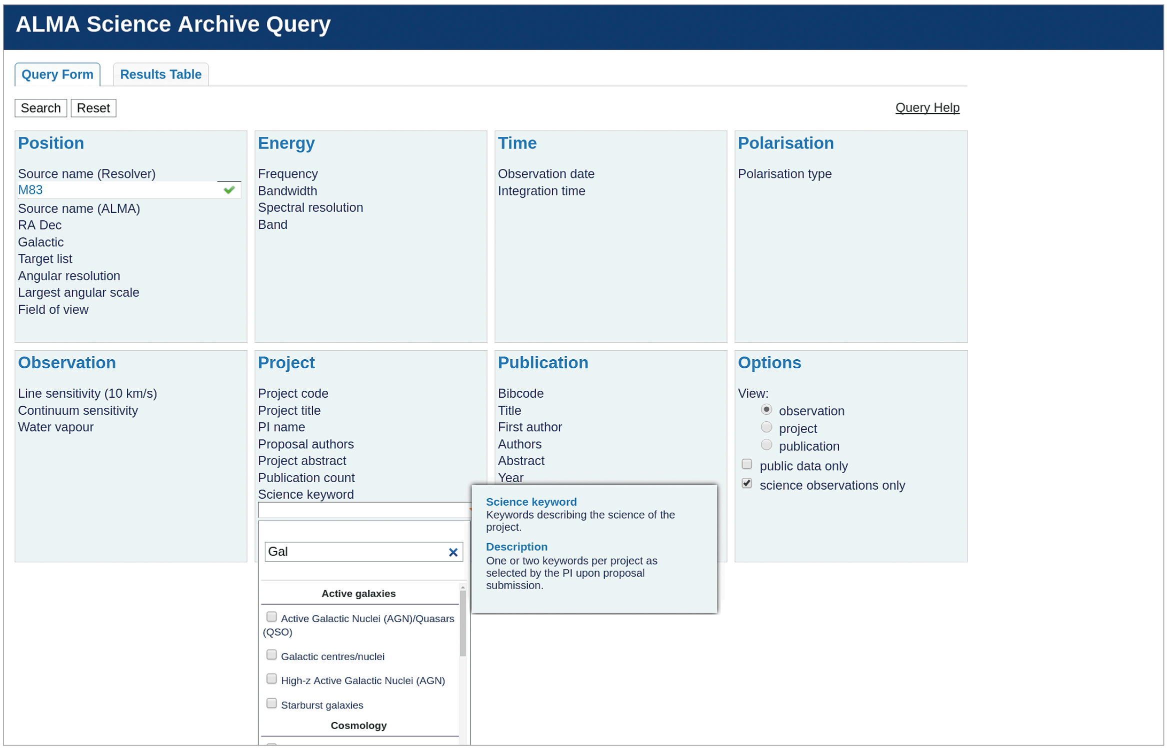

Figure 2. Query interface of the ALMA Science Archive with grouped keywords displaying self-opening input fields, unobtrusive tooltip help and the three different views for selection.

Querying

Searching astronomical data via search interfaces differs greatly from standard web searches, such as that provided by Google. Whereas the latter solve the problem “find words in a collection of text documents”, searches in astronomical archives are inherently multi-dimensional and many parameters are numerical rather than textual. In that sense, astronomical search engines are closer to product-finder search engines[4]. Moreover, the target audience of astronomical searches is extremely homogeneous and highly educated, as the vast majority of the users will hold degrees in astronomy or physics.

With this consideration in mind, our main design principles in the ALMA Science Archive are: access to the full parameter space; a maximally physical query; and, at the same time, minimal interaction cost. We consider each of these principles in turn.

Full parameter space

In the ALMA Science Archive we provide the capability to place query constraints simultaneously on observations, publications *and* proposals. Currently 31 input fields are available, of which 14 are numerical. For the input fields, a variety of operators can be used (equals, like, or, <, >, range, not, …). The query is completely unscoped, that is we do not require users to first query by position or object name, or even require any constraint at all. Hitting search without constraints will return the full holdings. This choice also has the positive side-effect that the multi-parameter search capability is automatically extended to all the more rarely used columns in the results table which do not show up on the query form, but for which we still provide a sub-filtering capability on the results page, like, for example, whether or not an observation is a mosaic or which antenna types were employed. The user can choose to display the results of any query in a view where one row corresponds to one observation, or to one project, or even to one publication. Given the homogeneous and educated audience, we intentionally chose not to provide an additional “basic” interface.

This multi-dimensional unscoped interface permits powerful queries to be executed. For example:

- show all public, but unpublished, observations. This enables the ALMA project to survey non-publishing PIs and to investigate the reasons why they could not publish (Stoehr et al., 2016);
- show all publications making use of full-polarisation data;
- show the proposals, data from which were used in publications having “molecular hydrogen” in the publication abstract;
- show all publications making use of data from the programme “Discs around high-mass stars”;
- show all observations of active galaxies reaching line sensitivities of 1 mJy/beam at 10 km s^{-1} resolution or continuum sensitivities of 0.1 mJy/beam.

Maximally physical query

Great efforts have been made to allow constraints to be placed on as many physical parameters as possible, according to the main properties a photon carries: position, energy, time and polarisation; see also Stoehr et al. (2014). Examples are the angular and spectral resolutions, the field of view, frequencies, bandwidth and the largest angular scale. In addition, users can now also query on the estimated sensitivity expected to

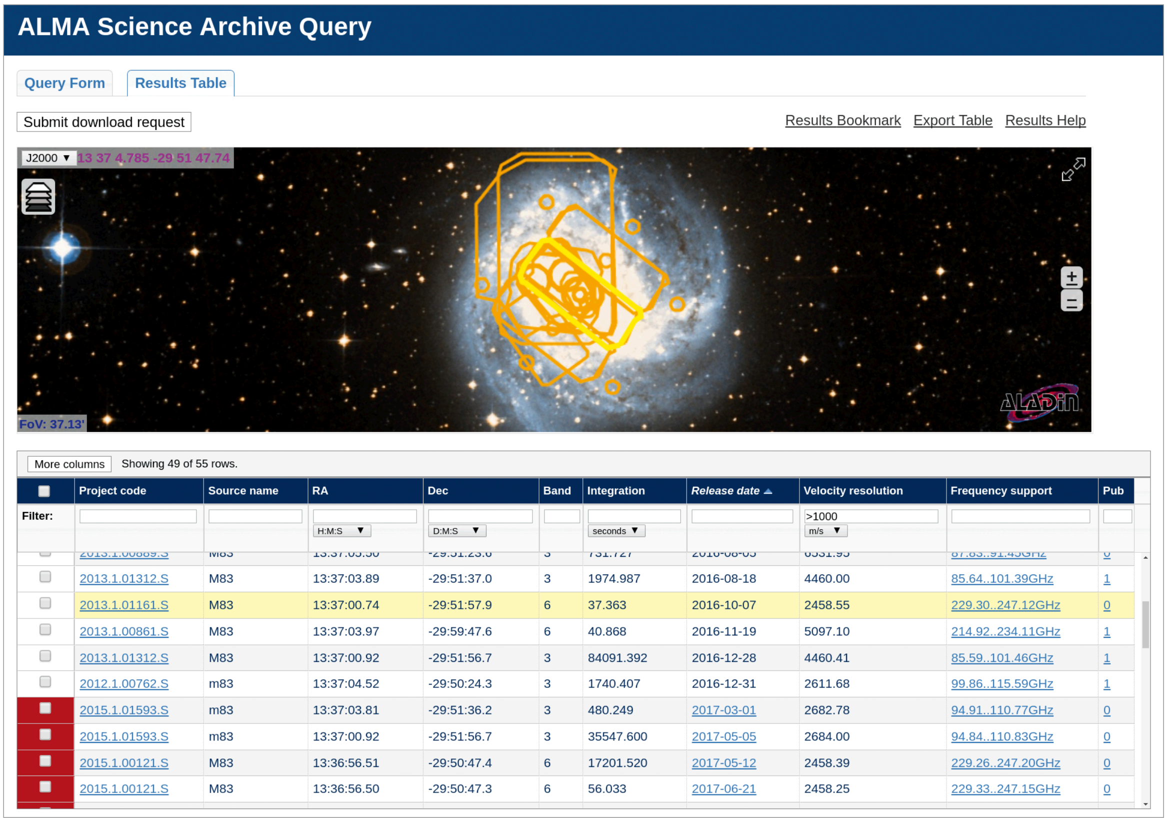

Figure 3. Results page for the ALMA Science Archive featuring footprint display on AladinLite and the results table with sub-filtering, sorting, adding/removing of any of the 37 columns and the bookmarking/exporting links.

be reached for line or continuum observations. This value, corresponding to the limiting magnitude in optical observations, is a particularly useful constraint. In addition, we capture the physical content of the observations from the users, offering the scientific keywords specified when the proposal was written and the scientific categories, as well as allowing searches through the titles and abstracts of the proposals and also publications making use of ALMA data.

Providing searches on physical concepts rather than observatory-specific jargon (for example, "angular resolution" rather than "array-configuration") is especially important, as ALMA's mission explicitly includes enabling non-radio astronomers to use the facility.

Minimal interaction cost

Although, as shown above, astronomical searches are quite different from typical web searches, wherever possible classical web-design principles have been applied. The most important of those principles is to reduce the interaction cost of the user to a minimum[5]. In the ALMA archive context this means reducing the cost of reading, identifying, as well as memorising, the structure and functionality of the interface. It also includes reducing the mouse travel distance and the number of mouse clicks, as well as ensuring that users should not be forced to leave the page during their interaction with the interface. A key to reducing interaction cost is to only provide the information to the users that they need at a given moment during the interaction with the interface (see also Stoehr et al., 2012 and Stoehr, 2017 in press) and to re-use the existing web knowledge and habits of users.

For the ALMA Science Archive interface (Figure 2), these principles mean, for example, to open input fields only when needed, to close them unless a value has been entered, to place the buttons always at the same location on the pages, to provide help directly on the page, to show information for each input field unobtrusively in a tooltip when the user is entering a value, and to have those tooltips contain clickable examples.

In contrast to the one-line interfaces of word-in-text searches, the knowledge of the search space ("what constraints can be given") on advanced interfaces is not trivially acquired by the users. Therefore the first task of any such interface must be to explain that search space. In order to reduce the interaction cost of this process, we visually group the concepts, order them by importance within the groups, remove everything that is unnecessary and make sure that the entire context fits onto the screens even of small laptops. The interface is trimmed for responses that are fast enough, so that the relevant context still resides in the user's short-term memory[6], further lowering the interaction cost.

Query results

The second step of every search is the exploration of the results to identify the assets in which the user is finally interested. For the ALMA Science Archive we show the observations in their astronomical context, using the observational footprints and the AladinLite[7] (Bonnarel et al., 2000; Boch & Fernique, 2014) sky view (Figure 3). In addition to zooming and panning, this software package allows the user to select sky backgrounds of different wavelength regimes. The sky view is fully integrated with the results table.

The results table developed by ALMA features sorting and reordering of the columns, sub-filtering and change of units on the fly, as well as addition or removal of any of the 37 currently available columns. For data still within their proprietary period, users can generate a calendar event to notify them when those data become public. For each observation, the number of related publications is displayed and a link takes the user to a list with the detailed description of those publications, including links to the Astronomical Data System (ADS[8]). The publication information is curated by ESO, NRAO and NAOJ library staff (Grothkopf & Meakins, 2015 and references therein). Hovering over the project code (or bibliography code) brings up a window with the title, author name and abstract of that proposal or publication.

Large result sets are streamed from the server to the user's browser, so the first results in the table are immediately visible; the table, however, remains interactive as more and more results are loaded in the background. The interface also memorises its entire state so that the query and result-table settings can be bookmarked, or the corresponding link can be sent to a colleague.

As no complete set of imaged ALMA products is available, the ALMA Science Archive query is based on the metadata of the raw data of the observations. Those metadata, however, are only available at a sub-observation level. In past years, this has led to the effect that for a single observation several result rows — and for mosaics up to several hundred rows — were returned to the users. Substantial efforts were deployed over the last two years to "collapse" these metadata into one row per observation by applying the same logic that the ALMA Pipeline would apply if it were to create imaging products from those raw data. While computing some of the values of these collapsed rows was rather simple (for example, the velocity resolution was set to the minimum of the velocity resolutions of the child observations), some computations were more challenging (such as the average integration time per position in a mosaic with overlapping pointings, or the spectral window pattern matching). An offspring of this development is the computation of footprints shown on the sky view (Figure 3).

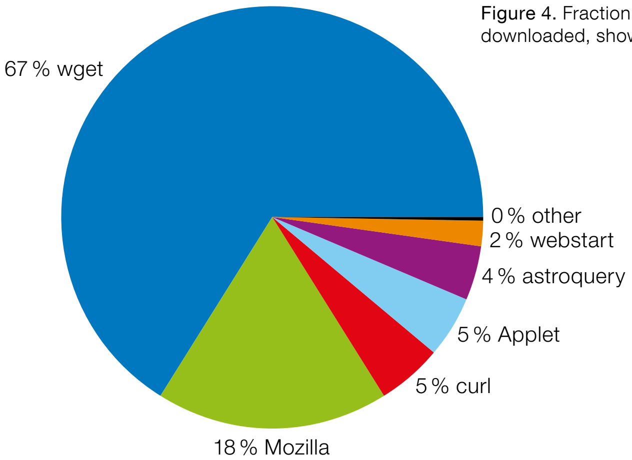

Figure 4. Fraction of the total amount of data downloaded, shown by download tool.

Data download

Once the desired assets are selected for download, the user is brought to the ALMA Request Handler. Here the related files are listed and the user is enabled to download specific files or select files by project, dataset or datatype. The names of the observation sets, as well as a list of the names of the contained sources, are given for each dataset to facilitate the selection process. This information is also available in an auto-generated readme file which also lists the full data directory names.

As the sizes of ALMA datasets are substantial, downloading in multiple parallel streams is a necessity. Depending on the user's internet browser and operating system, several download methods are offered. A download shell script, a Java applet, a Java webstart, and a page containing the list of the files which then can be fed to a browser plugin download manager, are all available.

The preferred download option is the shell script, which additionally allows the user to download the files to a different computer, such as directly to a processing environment. About two-thirds of the total amount of data retrieved from the ALMA archive is downloaded through download scripts (Figure 4).

In addition to the display on the web, the results of the query can be exported as Virtual Observatory (VO) VOTable, comma separated values (CSV) or tab separated values (TSV) files. Indeed full programmatic access is supported for querying as well as for download. This functionality is used, for example, by the community-developed software astroquery[9] which provides full ALMA archive access through Python. Besides being good practice, programmatic access is crucial for interoperable archives and data-mining.

Technology

The ALMA archive is at the centre of ALMA operations and all subsystems read and write from and to this central location (see, Stoehr et al., 2014). The main archive is located in Santiago, Chile at the Joint ALMA Observatory (JAO) and data are replicated from there to the three archives located at NRAO, NAOJ and ESO, which distribute them to the users. Each site only holds a single copy of each file and the sites serve as remote backups for each other.

Data are transferred over the network with dedicated network links of typically 100 Mbit s^{-1} and are stored in the ESO-developed storage system, the Next Generation Archive System (NGAS: Wicenec et al., 2001; Wicenec & Knudstrup, 2007).

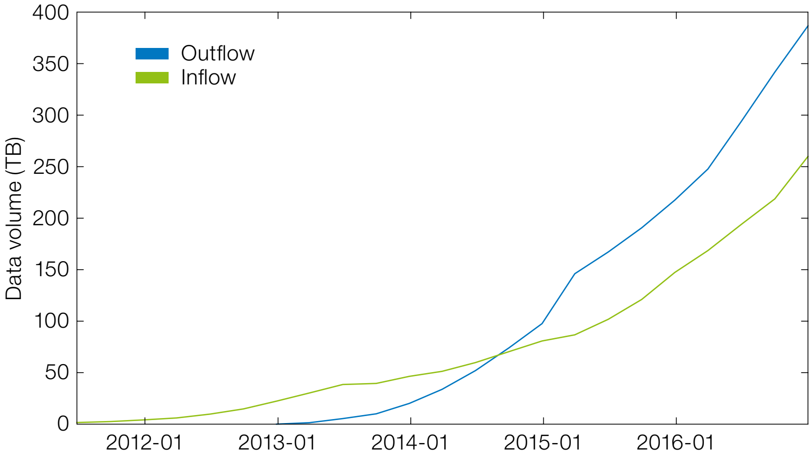

Figure 5. (Upper left) Cumulative data flow into the archive (green) and out of the archive (blue) in TB. The outflow could only be measured after the ALMA Request Handler was put in place in 2013. To February 2017, 386 TB have been delivered and 259 TB downloaded.

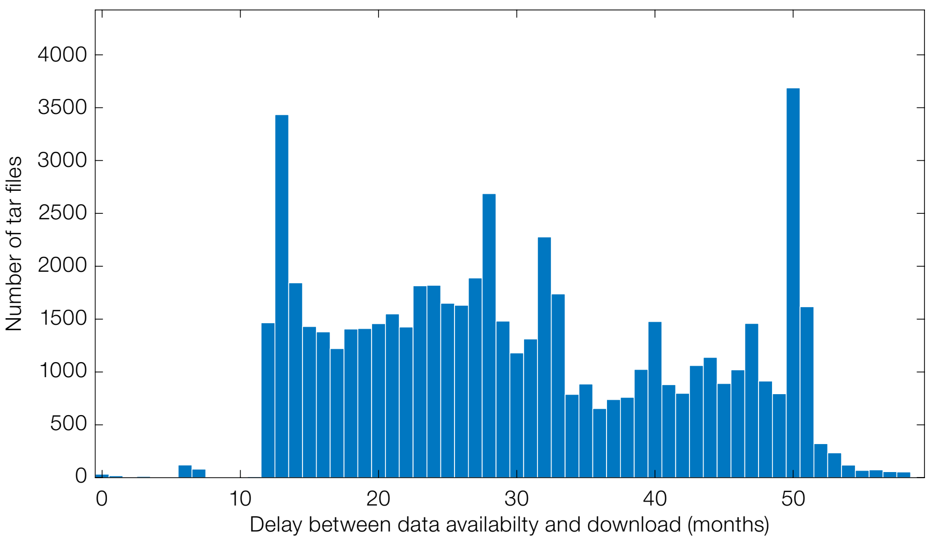

Figure 6. (Lower left) Time between the public availability of data and their download. Data are downloaded rapidly after they become public (12 months for most data, 6 months for Director's Discretionary Time data) and remain heavily requested for a long period.

The ALMA Science Archive is a single-page web application deployed on Apache Tomcat, built using Java, the Spring framework, JQuery and Oracle 12c. It is a deliverable of ESO to the ALMA project. We rely heavily on the OpenCADCTap[10] software package, which provides the VO layer on top of the database holdings. The query interface is a client to this VO layer using the Astronomical Data Query Language (ADQL[11]) as the interface language.

Holdings and statistics

At the time of writing, the ALMA Science Archive contains data from about 32 000 observations stored as 280 TB and distributed over 18 million files. Those data have led to 588 publications so far. Currently the ALMA Science Archive is growing by about 15 TB every month (see Figure 5). Data are downloaded quite quickly for archival research after they become public and remain of interest for a long period (Figure 6). This is especially significant given that ALMA is still a very young facility: the amount of data that is public for more than 40 months, for example, is much smaller than the amount of data that is public for more than 15 months.

Outlook

While the query functionality of the ALMA Science Archive can now compete with other astronomical archives, substantial work is still required over the next few years to improve the Results and Download contexts. These developments will include previews and access to individual files, progress in providing VO services, and integration of the two major related ALMA development programme tools, the data mining toolkit ADMIT and the visualisation package CARTA.

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Links

1 ALMA Science Archive: http://almascience.org/aq
2 Neural image caption generator: https://research.google.com/pubs/pub43274.html
3 LSST data management: http://euclidska.physics.ox.ac.uk/Euclid-SKA/160913/Tyson.pdf
4 Product-finder search engines: http://www.idealo.co.uk/filter/3751/laptops.html?q=notebook
5 User interaction cost: https://www.nngroup.com/articles/interaction-cost-definition/
6 Web and short-term memory: http://www.nngroup.com/articles/short-term-memory-and-web-usability
7 AladinLite: http://aladin.u-strasbg.fr/AladinLite
8 ADS: https://ui.adsabs.harvard.edu/#search/q=full%3A"ALMA"&sort=date%20desc%2C%20bibcode%20desc
9 Python astroquery: https://astroquery.readthedocs.io/en/latest
10 OpenCADCTap package: https://github.com/opencadc/tap
11 ADQL: http://www.ivoa.net/documents/latest/ADQL.html

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ALMA Band 5 Science Verification

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ALMA Band 5 (163–211 GHz) was recently commissioned and Science Verification (SV) observations were obtained in the latter half of 2016. A primary scientific focus of this band is the H_2O line at 183.3 GHz, which can be observed around 15 % of the time when the precipitable water vapour is sufficiently low (< 0.5 mm). Many more lines are covered in Band 5 and can be observed for over 70 % of the time on Chajnantor, requiring similar restrictions to those for ALMA Bands 4 and 6. Examples include the $H_2{}^{18}O$ line at 203 GHz, some of the bright (3–2) lines of singly and doubly deuterated forms of formaldehyde, the (2–1) lines of HCO^+, HCN, HNC, N_2H^+ and several of their isotopologues. A young star-forming region near the centre of the Milky Way, an evolved star also in our Galaxy, and a nearby ultraluminous infrared galaxy (ULIRG) were observed as part of the SV process and the data are briefly described. The reduced data, along with imaged data products, are now public and demonstrate the power of ALMA for high-resolution studies of H_2O and other molecules in a variety of astronomical targets.

One of the bands of the Atacama Large Millimeter/submillimeter Array (ALMA) that was not initially produced during construction of the observatory and was not available when the array was officially inaugurated in 2013 was Band 5, covering the frequency range 163–211 GHz (1.9–1.4 mm). Band 5 was one of the three frequency ranges originally envisioned for ALMA, but deferred from the construction project to the development programme. The other two are: the 35–50 GHz frequency range (Band 1, currently being produced by a consortium led by Academia Sinica Institute of Astronomy and Astrophysics [ASIAA] in Taiwan); and the lower portion of the 3 mm atmospheric transparency window (below 84 GHz), for which a new-technology, high-sensitivity receiver, dubbed Band 2+3 to cover the full 67–116 GHz band, is currently being developed in Europe.

ESO and several European partners (including Chalmers University in Sweden, the Science and Technology Facilities Council [STFC] in the UK and the University of Chile) were awarded funding by the European Commission under the EU's Sixth Framework Programme (FP6) to develop prototypes of Band 5. A set of six prototype receivers was produced by the Group for Advanced Receiver Development (GARD) at Chalmers University in collaboration with the Rutherford Appleton Laboratory (United Kingdom) under an EU FP6 contract and delivered to ALMA in 2012 (Billade et al., 2012). ALMA accepted the ESO proposal to outfit all 66 antennas with Band 5 receivers in 2012.

The production of the revised and optimised full complement of 73 Band 5 cartridges started in 2013, with production shared between GARD and the Nederlandse Onderzoekschool Voor Astronomie (NOVA), who were jointly responsible for the production and the integration of the Cold Cartridge Assembly of the receiver, and the National Radio Astronomy Observatory (NRAO) in the USA, who provided the Warm Cartridge Assembly. The receivers are dual polarisation SIS (superconductor insulator superconductor) mixers used in a sideband-separating (2SB) configuration and operated with all-reflective cold (< 4 K) optics. The measured system temperature of the production receiver is < 50 K over 80 % of the band (Belitsky et al., 2017), a figure significantly better than the original ALMA specifications for this receiver band, and achieved thanks to extensive optimisation work undertaken at GARD following the production of the six prototype receivers. Figure 1 shows one of the Band 5 cartridges.

Several of the six prototype Band 5 receivers were installed in other instruments, most notably on the Atacama Pathfinder EXperiment (APEX) telescope as part of the Swedish-ESO PI receiver for APEX (SEPIA) project. The SEPIA Band 5 receiver was commissioned at APEX in 2016 and Immer et al. (2016) describe the instrument and some of the commissioning and SV observations. Other Band 5 pre-production cartridges will be installed on the Atacama Submillimeter Telescope Experiment (ASTE) on Chajnantor, and on the Large Latin American Millimeter Array (LLAMA) in Argentina. One is kept at ESO for public display. The installation of the production Band 5 receivers started at ALMA during 2015 and 2016 and the first fringes were obtained in July 2015. At the time of writing 45 Band 5 cartridges have been delivered to the ALMA project and 32 of these are integrated in ALMA Front Ends.

Band 5 will be offered as a "standard mode" in all available array configurations (including the ALMA Compact Array, ACA) in ALMA Cycle 5. Current plans are for Band 5 to be available for science observations starting in the second half of the cycle (March 2018), following commissioning of all the receivers.

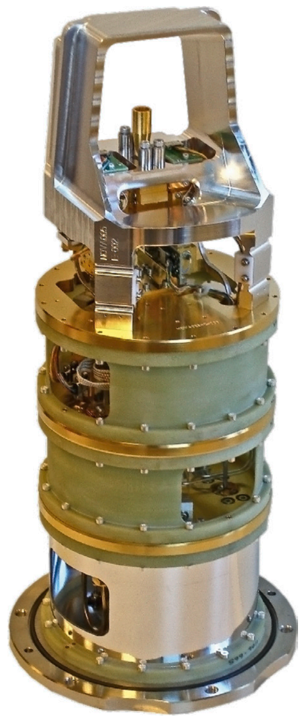

Figure 1. An assembled ALMA Band 5 receiver cartridge, shown courtesy of NOVA/GARD.

Band 5 Science Verification

ALMA Band 5 Science Verification (SV) observations took place from May to October 2016. In contrast to SV with Very Large Telescope (VLT) instruments, where proposals are solicited from the community, a set of targets are selected by an SV team composed of ALMA staff and scientists with the goal of providing a full end-to-end test and scientific validation of the new capability under operational conditions. The selection of targets and modes for SV focuses on testing challenging or novel calibration schemes to ensure smooth science operations. As per ALMA policy, the intention was to select targets with previous H_2O observations in order to enable a careful comparison with the ALMA results; in all cases the targets were also common to APEX SEPIA Band 5 observations. In the case of ALMA Band 5 SV, one extragalactic target with previously detected H_2O emission was selected — Arp 220, a prototypical luminous infrared galaxy — along with two Galactic targets: the molecular cloud complex near the Galactic Centre, Sagittarius B2, selected for a full-band spectral scan; and the evolved supergiant star VY CMa, chosen to demonstrate the line and continuum polarisation performance.

Observations of the H_2O ($3_{1,3}$–$2_{2,0}$) 183.3 GHz line are challenging even from the very high site on Chajnantor, since the precipitable water vapour (PWV) is only below 0.5 mm about 15 % of the time (~50 days per year). Figure 2 of Immer et al. (2016) shows the atmospheric transmission through the 183.3 GHz H_2O line as a function of PWV; a PWV < 0.5 mm ensures a transmission in the line peak of > 35 %, with PWV of 0.3 mm required for transmission > 50 %. There are a number of other molecular lines of interest in Band 5, including HCN(2–1) at 177.3 GHz, HNC(2–1) at 181.3 GHz, CS(4–3) at 196.0 GHz, CH_3OH(4–3) at 193.5 GHz and several SiO (J = 4–3) lines between 171.3 and 173.7 GHz, but none of these is seriously affected by the H_2O transmission unless the PWV is large (≳ 2 mm). See Table 1 and Figure 2 of Immer et al. (2016) for an extended list of molecular lines in the band.

An additional aspect of the SV observations was to test the compatibility of the standard ALMA observing software with Band 5 observations, and to determine the best calibration parameters to be used in Band 5 Cycle 5 observations. As Band 5 had never been used with the ALMA Observing Tool (OT) before, it was important to check that Scheduling Block (SB) generation worked as expected and that the SBs could be submitted to the archive and successfully executed. All SV observations were carried out with SBs created using an SV version of the OT, and observations were performed in a pre-release version of the Cycle 5 ALMA control system.

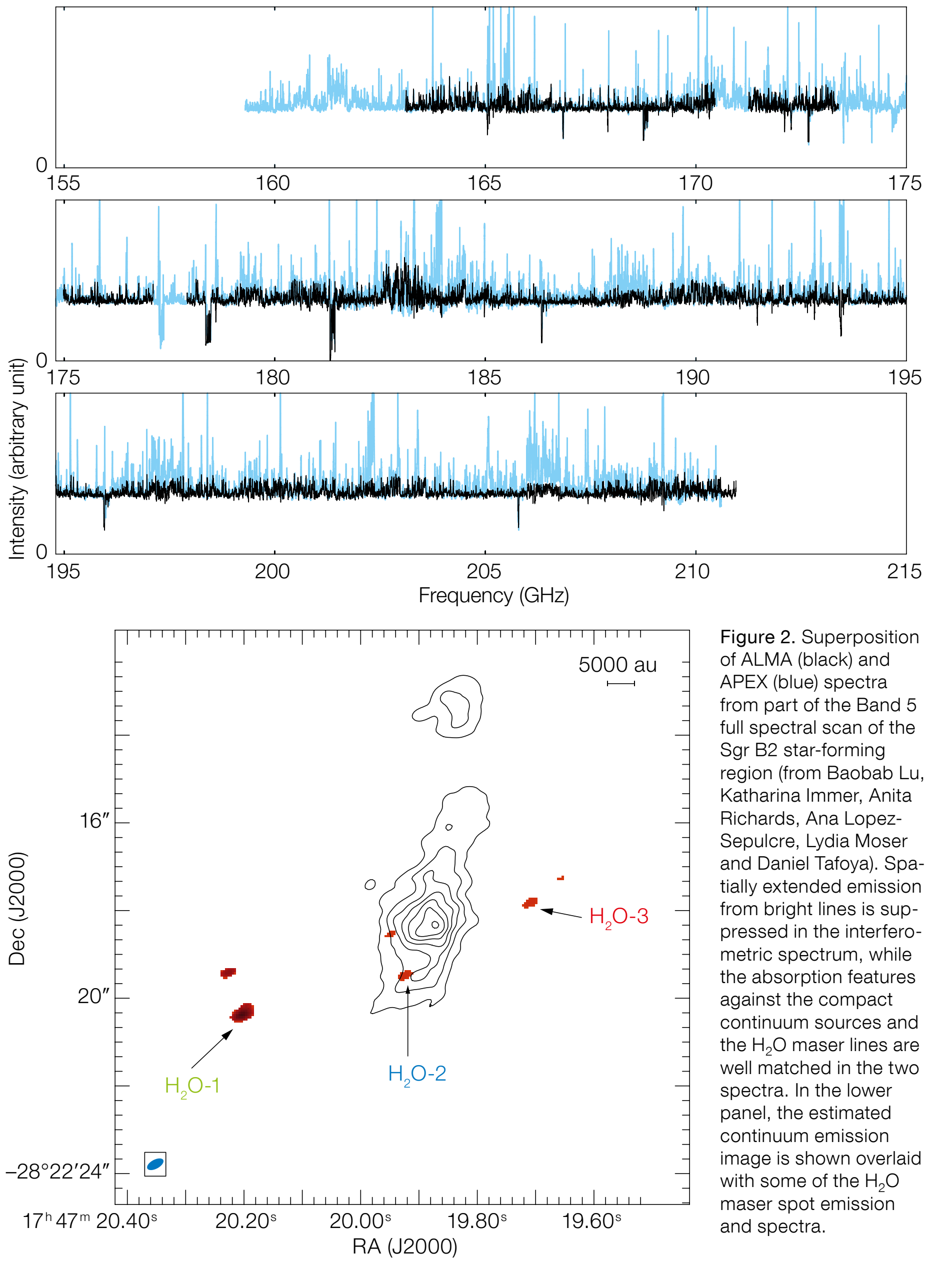

Figure 2. Superposition of ALMA (black) and APEX (blue) spectra from part of the Band 5 full spectral scan of the Sgr B2 star-forming region (from Baobab Lu, Katharina Immer, Anita Richards, Ana Lopez-Sepulcre, Lydia Moser and Daniel Tafoya). Spatially extended emission from bright lines is suppressed in the interferometric spectrum, while the absorption features against the compact continuum sources and the H_2O maser lines are well matched in the two spectra. In the lower panel, the estimated continuum emission image is shown overlaid with some of the H_2O maser spot emission and spectra.

SV observations

Sgr B2

Sagittarius (Sgr) B2 is a massive and dense high-mass star-forming complex situated at a projected distance of ~120 pc from the Galactic Centre. The cloud is well known for its rich chemistry and has been extensively studied with submillimetre telescopes, including APEX and ALMA, with the goal of detecting complex organic molecules and understanding the chemical processes in the dense interstellar medium (for example, Belloche et al., 2013). Sgr B2 had already been observed in Band 5 with APEX SEPIA (Immer et al., 2016) so could provide an ideal comparison with the ALMA data.

The almost complete range of Band 5 was observed with 13 receiver tunings and a hybrid array, consisting of 8–12 12-metre antennas with baselines of up to 1.6 km, with four 7-metre antennas included for some observations. Given the complexity of the source morphology, the limited number of antennas used and the sparse coverage of the (u,v) plane with the limited set of available baselines, the imaging of this dataset is challenging, and the image fidelity is relatively low compared to typical ALMA observations. The importance of this SV observation was to provide a complete spectral scan of the whole of Band 5 to test the ability to calibrate across the full band in varying atmospheric absorption conditions.

Figure 2 (upper) shows the ALMA and SEPIA spectra overlaid. A wealth of molecular lines is revealed at a velocity resolution of ~1 km s^{-1}, many of which remain to be identified. For part of the observing time the H_2O transmission was low enough to map some water maser emission clumps associated with the massive star formation (Figure 2, lower). The comparison between the APEX and ALMA spectra shows that the brightest lines, associated with more extended emission, are not fully recovered in the interferometric spectrum, because of the aforementioned limitations in the (u,v) coverage. The compact structures, including all absorption lines against the bright and compact continuum emission, are well matched.

VY CMa

VY Canis Majoris is a red supergiant star of spectral type M5 in a phase of strong mass loss (< 10^{-4} $M_{\odot}$ yr^{-1}). The star is very extended and of high luminosity (~ 3 × 10^5 $L_{\odot}$, for a distance of 1.2 kpc) and the 25–32 $M_{\odot}$ progenitor star is now evolving blueward in the Hertzsprung-Russell diagram (Wittkowski et al., 2012).

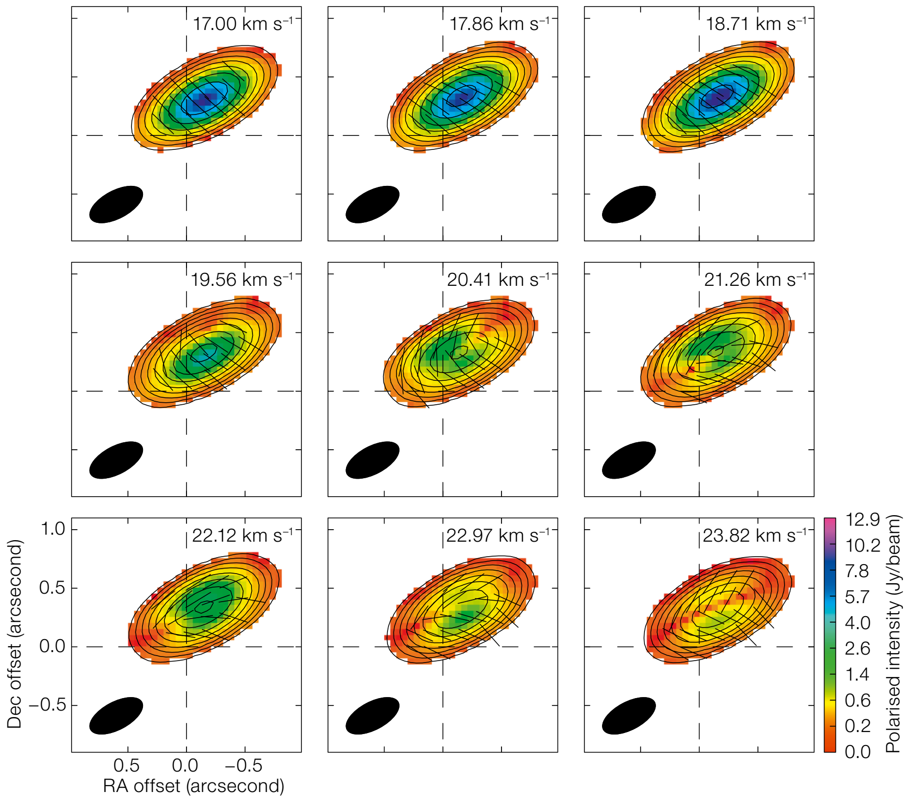

Figure 3. Spatially resolved velocity slices of the polarisation vectors in VY CMa superimposed on the polarised intensity image for the SiO maser line around 172.5GHz (from a report released with the ALMA data by Iván Martí-Vidal, Wouter Vlemmings and Tobia Carozzi[2]).

It is expected to eventually explode as a core collapse supernova. It has a complex, extended and outflowing dusty and molecular envelope with H_2O and SiO maser emission detected. The SV observations concentrated on measuring the polarisation in continuum and in the H_2O and SiO maser lines (at 183.3 and around 172.5 GHz, respectively). Fifteen ALMA 12-metre antennas and baselines up to 0.48 km were employed and again there were previous APEX observations with which to compare.

This is the first ALMA SV line polarisation dataset obtained and it was used to check the observation and data reduction procedures for this important observing mode, expected to be used for a variety of science cases and astronomical targets. For supergiant stars like VY CMa, it is anticipated that ALMA line polarisation observations will make transformational advances in understanding stellar magnetic field strength and morphology. This may be important for understanding the mass-loss process from these stars, and the structures observable in the circumstellar envelopes. For lower mass stars, such as those on the Asymptotic Giant Branch, ALMA polarisation observations may additionally provide information on the processes leading to planetary nebulae. In the SV dataset, one of the results is that both the continuum and the SiO and H_2O maser emission towards VY CMa are confirmed to be polarised. Maps of the polarisarisation vectors in SiO maser emission are shown in Figure 3.

Arp220

Arp 220 is the closest (at ~ 78 Mpc) ultra-luminous infrared galaxy (~ 4 × 10^{12} $L_{\odot}$) representing an ongoing merger. The core has a very high star formation rate and is a rich source of molecular emission. It has been extensively observed at mm and radio wavelengths and displays H_2O maser emission (at 22, 183 and 325 GHz). The 183 GHz water emission was previously observed using the Institut de Radioastronomie Millimétrique (IRAM) 30-metre telescope and APEX.

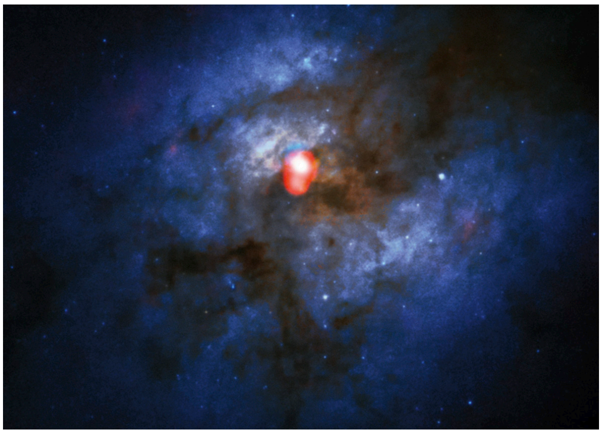

Figure 4. Composite sub-mm/optical image of Arp 220 showing the Band 5 emission including HCN, CS, SiO and H_2O from the SV observation of the nuclear star forming region (in red) on top of an image from the NASA/ESA Hubble Space Telescope (blue/green). West is up and north left in this composite. The ALMA image was provided by Sebastien Muller and Sabine König. See Release eso1645 for details.

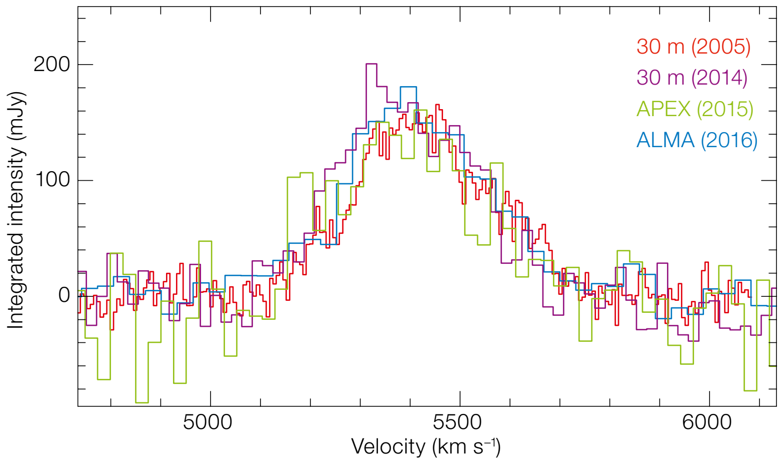

Figure 5. The H_2O 183.3 GHz line as observed with the IRAM 30-metre telescope in 2005 (Cernicharo et al., 2005) and 2014, with SEPIA on APEX in 2015 (Galametz et al., 2016) and with ALMA in 2016 (König et al., 2017), displaying the relative constancy of the line profile. From König et al. (2017).

Arp 220 has a double nucleus with the peaks of molecular emission separated by 1.1 arcseconds and the Band 5 observations (beam size 0.7 arcseconds) resolved the H_2O emission into the east and west nuclei (see Figure 4). The western component is brighter while the eastern one has a steep velocity gradient. König et al. (2017) compared the H_2O 183.3 GHz line profile with previous observations using the IRAM 30-metre telescope (Cernicharo et al., 2006) and the SEPIA Band 5 receiver on APEX (Galametz et al., 2016). The line profiles are remarkably similar over a period of > 10 years (see Figure 5). This is perhaps unexpected for maser lines, which characteristically change in strength on timescales of months to years. It is therefore suggested that the H_2O profile represents the emission of many unresolved maser spots within the star-forming complex, so that, while individual masers vary, the aggregate profile does not (König et al., 2017).

Data Release

After the initial data collection and assessment, an intensive workshop was held at Chalmers University, Sweden in October 2016 where participants from across the European ALMA Regional Centre (ARC) worked to solve the calibration problems and finalise the calibration and data release products. On 7 December 2016, the Band 5 raw data, calibrated data and reference images, as well as the calibration scripts and detailed documentation explaining the imaging and calibration procedures, were publicly released on the ALMA SV page[1]. At the Band 5 Workshop in February 2017 (see the following article by de Breuck et al., p. 11), analysis and results from these SV observations were presented and discussed.

These SV observations allowed us to validate and release the science operations procedures to obtain successful ALMA Band 5 observations and resulted in the inclusion of Band 5 as a standard mode in the Cycle 5 call for proposals. The datasets are now being used by astronomers in the community to perform scientific analysis and to prepare for their own observing proposals in the forthcoming ALMA Cycle.

Acknowledgements

Obtaining, validating and releasing the ALMA Band 5 SV data was a team effort involving a large number of people at ESO, the EU ARC Network and the Joint ALMA Observatory (JAO). We thank for their key contributions Tobia Carozzi, Simon Casey, Sabine König, Ana Lopez-Sepulcre, Matthias Maercker, Iván Martí-Vidal, Lydia Moser, Sebastien Muller, Anita Richards, Daniel Tafoya, Wouter Vlemmings, Allison Man, John Carpenter, Paulo Cortes, Diego Garcia, Itziar de Gregorio, Antonio Hales, Violette Impellizzeri, Andres Felipe Perez Sanchez, Neil Phillips, Adele Plunkett, Giorgio Siringo, Satoko Takahashi, the JAO Extension and Optimisation of Capabilities (EOC) Team and the JAO Department of Science Operations (DSO) team members who performed the observations. The fantastic Band 5 receivers we have on ALMA would have not been possible without the preproduction effort funded by the EU FP6 at GARD and RAL, and without the cartridge optimisation and production effort at GARD, NOVA, and NRAO, and the Integration and Verification team on site in Chile supported by ESO, with contributions from the National Astronomical Observatory of Japan (NAOJ). We thank Jeremy Walsh for his work on this article.

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Links

[1] ALMA SV Band 5 data release: targets: https://almascience.eso.org/alma-data/science-verification
[2] Band 5 Polarisation Calibration Information: https://almascience.eso.org/almadata/sciver/VYCMaBand5/VYCMa_Band5_PolCalibrationInformation.pdf

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Report on the ESO Workshop

Getting Ready for ALMA Band 5 — Synergy with APEX/SEPIA

held at ESO Headquarters, Garching, Germany, 1–3 February 2017

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[1] ESO

The workshop provided an overview of the wide range of results from the first two years of science operations with the ALMA Band 5 (163–211 GHz) receiver in the Swedish ESO PI Instrument for APEX (SEPIA) ahead of the ALMA Cycle 5 call for proposals, when the Band 5 receivers will be offered for the first time. The frequency range of the Band 5 receiver has never been fully covered by existing receivers; the talks presented at the workshop illustrate the importance of several lines in this frequency range that provide crucial diagnostics of the interstellar medium.

SEPIA, the Swedish ESO PI Instrument for the Atacama Pathfinder EXplorer (APEX) was developed around a pre-production Band 5 receiver (157–212 GHz) built for the Atacama Large Millimeter/submillimeter Array (ALMA). It was installed on APEX in early 2015 (Immer et al., 2016), and is already being used by European astronomers to reveal the new science that can be done in this relatively unexplored frequency band. The Band 5 receivers are in the process of being installed in ALMA and the previous article (Humphreys et al., p. 7) describes the Science Verification (SV). The timing was therefore right for a workshop on the Band 5 science already achieved with SEPIA.

The goal of the meeting was to discuss and highlight the role of APEX as an ALMA complement and to encourage European ALMA users to focus on the science that will be enabled by the new Band 5 receivers ahead of the ALMA Cycle 5 call for proposals. The workshop was attended by more than 50 astronomers and submillimetre instrument builders (see Figure 1) and also featured some SEPIA science with the Band 9 receiver.

Development of the Band 5 receivers

As explained by Victor Belitsky, who gave the opening invited talk, the idea of building a receiver to cover the frequency gap between ALMA Bands 4 and 6, and across the 183.3 GHz atmospheric H_2O absorption line, started in 2005. Thanks to a specific grant as part of the European Union's Sixth Framework Program (FP6), a first set of six "pre-production" receivers was built by the Group for Advanced Receiver Development (GARD) at the Chalmers University of Technology in Gothenburg in collaboration with the Rutherford Appleton Laboratory (Billade et al., 2012). After successful testing at ALMA, a full set of optimised receivers was built by GARD and the Nederlandse Onderzoekschool Voor Astronomie (NOVA) in Groningen, with the local oscillators (LO) and warm electronics built by the National Radio Astronomy Observatory (NRAO) in the USA.

Giorgio Siringo from the Joint ALMA Observatory (JAO) gave a detailed progress report of the installation and verification of the Band 5 receivers at ALMA. Production and delivery of the receiver cartridges is expected to be completed (including all spares) by the end of 2017, while completing the installation and verification for use within the ALMA antennas depends on the scheduling of Front End maintenance at the Observatory. The current estimate is that Cycle 5 science operations for Band 5 receivers will commence in March 2018 (see Humphreys et al., p. 7).

Evolved star science with Band 5

One of the areas where the Band 5 receiver has already made a significant impact in its two years of science operations at APEX is the field of evolved stars (overview talk by Elvire De Beck). The outer layers of these stars are laboratories where a wide range of molecules are formed and fed into the interstellar medium (ISM) through stellar winds. Although no CO lines are present in

Luis Calçada/ESO

Figure 1. The participants at the APEX/ALMA Band 5 workshop outside the ESO Headquarters building.

Band 5, there are many other important molecules such as HCN, HNC, HCO^+ (talk by Karl Menten), H_2S (Taïssa Danilovich), and many others, including key isotopomers to study fractionation, which are found in spectral line surveys (Elvire De Beck). By combining the constraints from these lines with spectral surveys at other frequencies, one is now obtaining a full inventory of the circumstellar gas. This in turn allows the chemical state to be constrained in the various classes of evolved stars (for example, split by chemical types or density regimes), and their different evolutionary paths.

One important advantage of Band 5 is that the bright H_2O and SiO maser transitions at 183.3 and ~173 GHz can be observed simultaneously (Liz Humphreys). This allows the physical conditions, dynamics and even the magnetic field strengths and morphologies throughout the outflow to be traced. One of the interesting new applications of the dual polarisation Band 5 receiver in SEPIA was to look for polarised emission in SiO and H_2O masers. As SEPIA is located in the Nasmyth A cabin without a de-rotator, recovering the polarisation angle is very complicated. However, one can still look at the difference between the two polarisations, and can thus identify which of the maser lines are significantly polarised. Humphreys et al. (submitted to A&A) have indeed found that only some components of the SiO masers are polarised, while the H_2O emission is not.

The ability to perform accurate line and polarisation observations is a key strength of the ALMA Band 5 receiver, as shown by the SV data for VY CMa (Humphreys et al., p. 7). In this source, ALMA data showed that both SiO and H_2O (as well as the continuum) show polarised emission. The combination of APEX surveys with ALMA high-resolution follow-up in this area is thus expected to produce transformational results in the coming years.

The 183.3 GHz water line

The most challenging Band 5 observation is across the $3_{1,3}$–$2_{2,0}$ atmospheric absorption line of H_2O centred at 183.3 GHz. However, with precipitable water vapour (PWV) < 0.5 mm, this line does become observable from Chajnantor, and is a powerful probe of the ISM, as water controls the chemistry of many other species (Floris van der Tak). The detection of H_2O in protoplanetary disks will allow us to determine and study the snowline, a key missing piece of the puzzle to understand the distribution of life-supporting volatiles in planetary atmospheres.

Nevertheless, such observations may be challenging even with the sensitivity and spatial resolution of ALMA (Michiel Hoogerheijde and Ruud Visser), requiring significant time investment for this key science goal of ALMA Band 5. As explained by John Carpenter, Band 5 observations of discs will also offer many other lines that will provide powerful diagnostics of turbulence, the snowlines of various volatiles, nitrogen fractionation, deuteration and ionisation. As a byproduct of any line observations of discs with ALMA, it will be possible to observe the dust emission at high spatial resolution to probe grain properties using continuum and polarisation measurements.

Friedrich Wyrowski reported strong H_2O detections in hot molecular cores using SEPIA. When combined with other water lines at higher frequencies, in particular the optically thin $H_2{}^{18}O$ line at 203 GHz, still within the Band 5 receiver frequency range, one can determine the relative roles of maser versus thermal excitation of water.

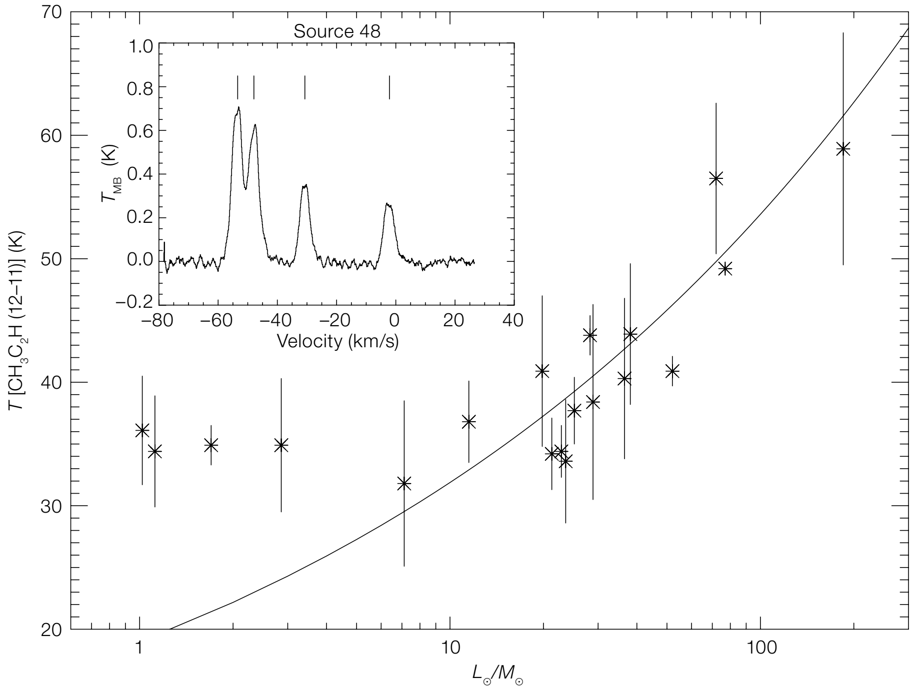

Figure 2. CH_3C_2H(12–11) gas temperature as a function of the luminosity to mass ratio (L/M) for high-mass protocluster candidates from the Hi-GAL survey. The inset shows one of the SEPIA CH_3C_2H spectra (adapted from Molinari et al., 2016).

When looking for water in external galaxies, even a small redshift helps to improve the atmospheric transmission. However, special care will have to be taken to properly calibrate broad emission lines across the varying atmospheric absorption in the shoulders of the atmospheric water line. As discussed by Immer et al. (2016), the application of APEX offline calibration is required across the water absorption line to avoid large amplitude discrepancies across the SEPIA passband. Upgrades of the APEX OnlineCalibrator are planned to provide this higher-resolution calibration by default.

SEPIA observations of extragalactic water have led to the confirmation of the previously reported H_2O line in the ultra-luminous infrared galaxy Arp 220 at z = 0.018 (Galametz et al., 2016), and a weaker tentative detection in IRASF17207-0014 at z = 0.043 presented by Zhi-Yu Zhang (Yang et al., in prep.). The Arp 220 system was also observed as part of the ALMA Band 5 SV (Humphreys et al., p. 7). The comparison of the APEX, ALMA and previous observations of the water line shows a remarkable stability (in terms of intensity and line profile) of this masing line in Arp 220 (König et al., 2017); see Figure 5 of Humphreys et al., p. 7.

Other gas tracers in Band 5

The first spectral line surveys in Band 5 have already shown a remarkable richness of molecular lines, as illustrated, for example, by the Sgr B2(N) spectrum observed with both ALMA and SEPIA (Fig. 5 of Humphreys et al. p. 10), or the D-Dor survey shown in De Beck's talk. Apart from the aforementioned H_2O and $H_2{}^{18}O$ lines, which probe the location of the snowline and the thermal structure in disks, the SO_2 line can be used to determine the shock chemistry and system geometry, while the CH_3OCH_3 and C_2H_5CN lines provide information on the grain surface chemistry (van der Tak). The CH_3C_2H line has also been used as a powerful temperature probe for dense gas (Molinari et al., 2016). By selecting dense clumps from the Hi-GAL survey of our Galaxy, Sergio Molinari and Manuel Merello reported a remarkably strong correlation between the CH_3C_2H line strength and the luminosity–mass ratio (Figure 2).

The presence of important H, C, N, O, and S isotopomers for several key molecules in this band will also allow to extend important work on element fractionation in various phases of the interstellar medium. Examples discussed at the workshop included (besides $H_2{}^{18}O/H_2O$ studies) the studies of H fractionation using some of the (3–2) lines of singly and doubly deuterated formaldehyde (Sarolta Zahorecz) and potentially the study of the $^{14}N/^{15}N$ ratio using the (2–1) lines of HNC, HCN and N_2H+ isotopomers (Figure 3).

In star-forming regions, the brightest lines in Band 5 are the 2–1 transitions of HCN, HNC and HCO^+. In a pilot survey of pointed observations within the LMC and SMC, Maud Galametz found large spatial variations between the HCO^+(2–1) and the other lines such as HCN, HNC and CO. A first mapping campaign has been started to better probe the origin of these variations (see Figure 4).

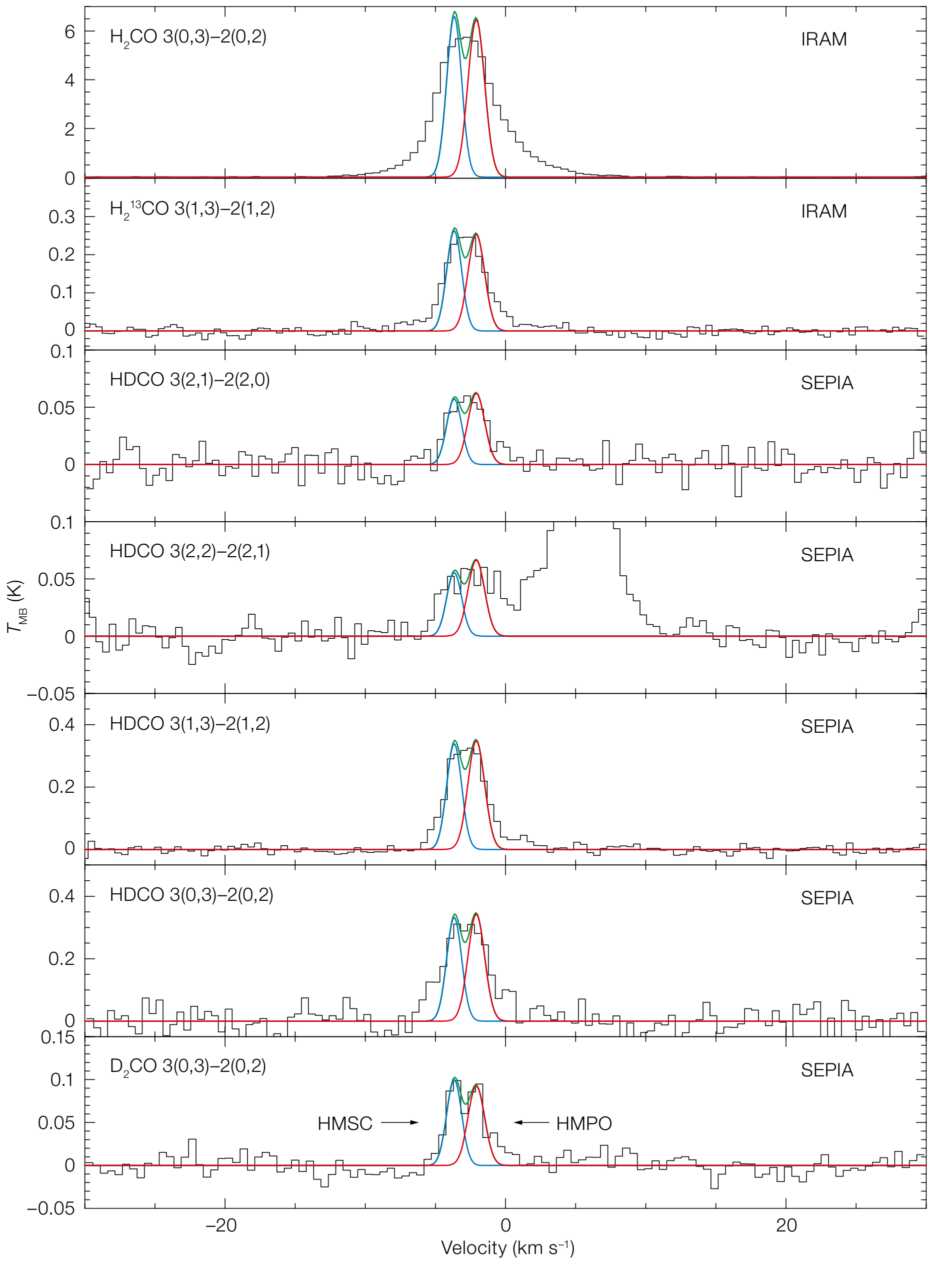

Figure 3. SEPIA HDCO and D_2CO spectra for the high-mass star-forming region AFGL 5142, compared with H_2CO and $H_2{}^{13}CO$ measurements from the Institut de Radioastronomie Millimétrique (IRAM) 30-metre telescope (adapted from Zahorecz et al., 2017). The blue profile is associated with the high-mass starless cores (HMSC) and the red profile with the high-mass protostellar objects (HMPO).

The high redshift Universe

Kirsten Knudsen and Maria Strandet summarised the role of Band 5 for high-redshift science, highlighting respectively the CO and fine structure lines that move into the frequency range of Band 5 for different redshift ranges. Band 5 extends the redshift coverage of the CO(2–1) line out to z = 0.46, and SEPIA has already started to fill the existing redshift gap (from Edo Ibar). To cover the CO spectral line energy distribution, continuous frequency coverage is essential (from Bitten

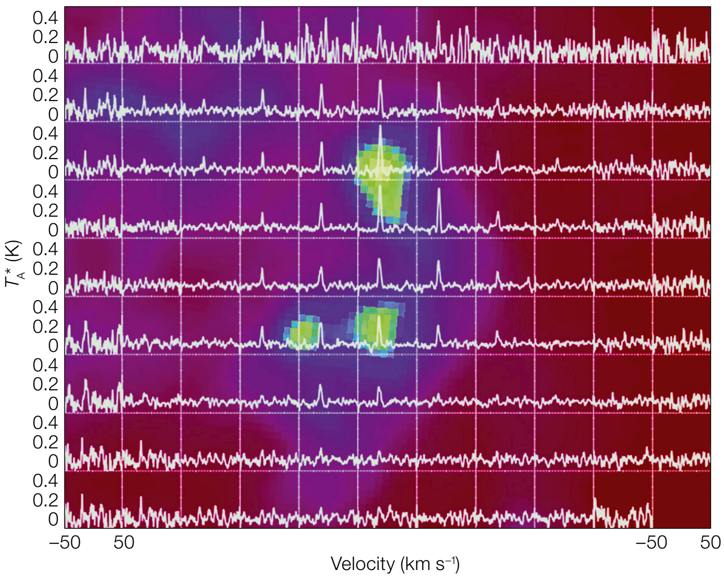

Figure 4. An HCO+(2–1) map of the Large Magellanic Cloud region N159W obtained with APEX/SEPIA Band 5 (Galametz et al., in prep.).

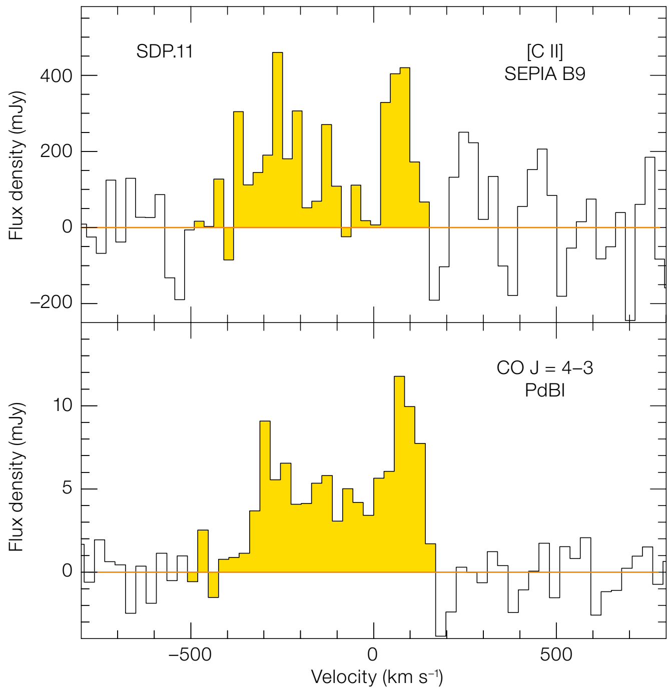

Figure 5. The [C II] 158 μm line detected with the Band 9 receiver of SEPIA in the z = 1.8 dusty star-forming galaxy SDP.11 (Zhang et al., in prep.). The velocity profile in this short SEPIA observation is fully consistent with the IRAM Plateau de Bure CO(4–3) data of Oteo et al. (2017).

Gullberg). For fine-structure lines, the most important lines shifting into Band 5 at $1.33 < z < 2.11$ and $2.84 < z < 4.13$ are the [C I] 609 μm and 370 μm lines, respectively. Paola Andreani and Matt Bothwell highlighted the importance of the [C I] line as an alternative tracer for the H_2 mass, and reported several SEPIA detections. By filling the frequency gap in the ALMA coverage, the SEPIA Band 5 receiver has also manifested itself as an ideal follow-up instrument for ALMA, confirming ambiguous redshifts obtained with ALMA Band 3 spectral scans (Strandet et al., 2016).

Synergy with Band 9

While the main topic of the meeting was the Band 5 receiver, the other receiver currently installed inside SEPIA, a Band 9 (600 to 722 GHz) ALMA receiver, has a very similar synergy with ALMA.

A number of talks presented first results, such as the intriguing ArH+ line results in the Crab Nebula (Ilse De Looze) and the 658 GHz vibrationally excited water lines presented by Alain Baudry. Even for extragalactic science, the Band 9 receiver now has sufficient bandwidth to allow the detection of broad emission lines, such as the z ~ 1.9 [C II] lines observed during SV by Zhi-Yu Zhang (Figure 5), and the tentative [O III] 88 μm detections by Carlos De Breuck. The Sgr B2(N) spectral scan highlighted the difficulty of using the current double sideband (DSB) receiver for line-rich sources, due to overlapping signal coming from the two sidebands (Katharina Immer). With future upgrades to a sideband-separating receiver and a doubling of the spectral bandwidth, we can hope for an APEX pathfinding role for ALMA in this band too.

Practical sessions

As Band 5 has some special features due to the presence of the deep atmospheric absorption feature, the ALMA Regional Centre and APEX staff explained to the participants how to optimally prepare for their Service Mode observations. Users should in particular pay attention to the placement of the image band, as this may have little transparency if placed near the 183 GHz band. The new features in both the ALMA Observing Tool and the APEX Phase 2 web submission tool were also presented. As the ALMA and APEX archives are also growing steadily, demonstrations were given of how to optimally use the query forms. Future developments (for example, better visualisation tools) were also mentioned on how to better mine the ALMA and APEX data archives.

Acknowledgements

The practical sessions would not have been possible without the help of the tutors Francisco Montenegro, Kalle Torstensson, Paulina Venegas, Claudio Agurto, Suzanna Randall and Felix Stoehr. Thanks go to Baobab Lu for his help collecting the presentations from the speakers, to Rein Warmels for help setting up the web pages, and especially to Stella Klingner for the smooth organisation of the workshop.

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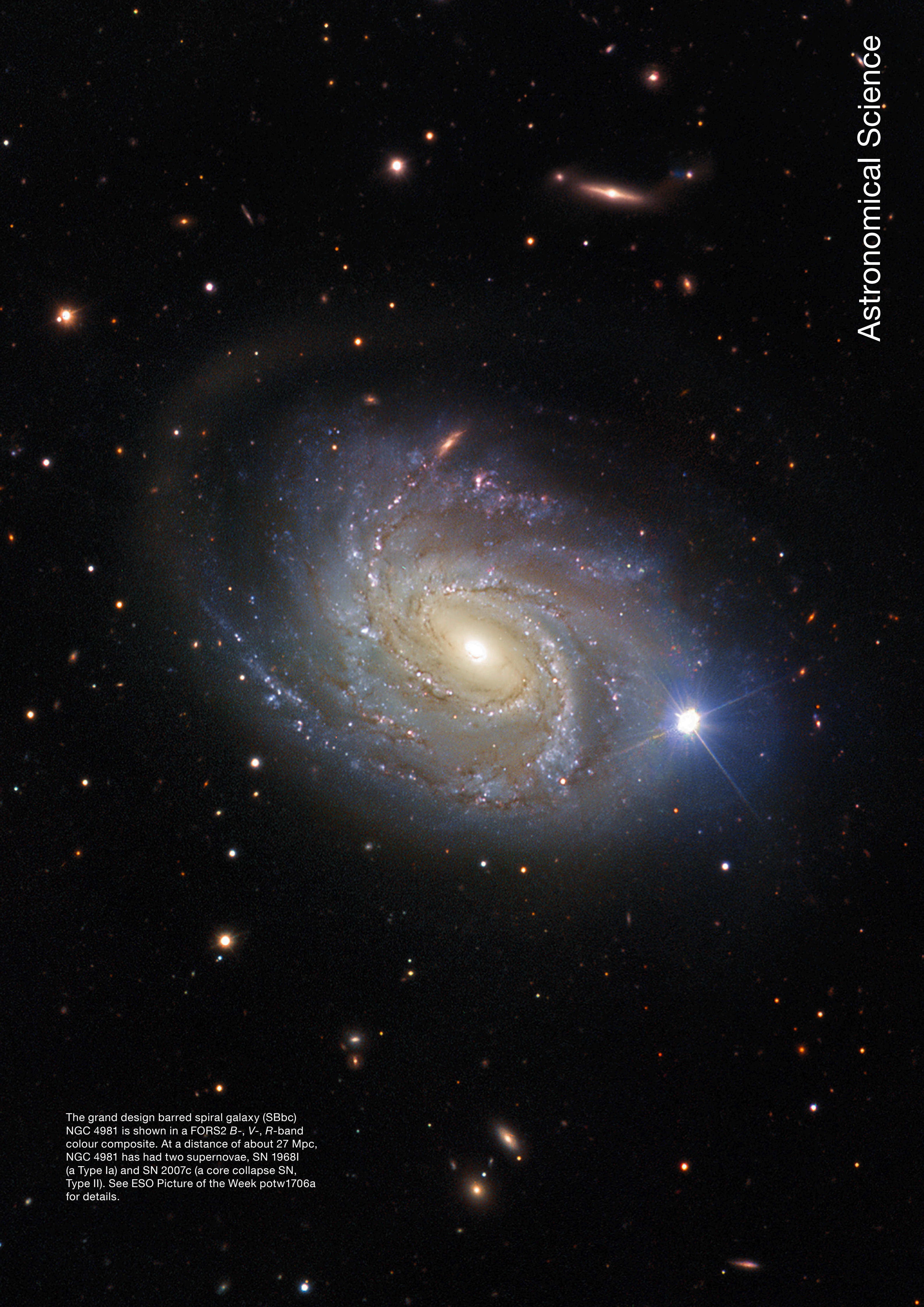

The grand design barred spiral galaxy (SBbc) NGC 4981 is shown in a FORS2 *B*-, *V*-, *R*-band colour composite. At a distance of about 27 Mpc, NGC 4981 has had two supernovae, SN 1968I (a Type Ia) and SN 2007c (a core collapse SN, Type II). See ESO Picture of the Week potw1706a for details.

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Minor Planet Science with the VISTA Hemisphere Survey

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We have carried out a serendipitous search for Solar System objects imaged by the VISTA Hemisphere Survey (VHS) and have identified 230 375 valid detections for 39 947 objects. This information is available in three catalogues, entitled MOVIS. The distributions of the data in colour-colour plots show clusters identified with the different taxonomic asteroid types. Diagrams that use (*Y*–*J*) colour separate the spectral classes more effectively than any other method based on colours. In particular, the end-class members A-, D-, R-, and V-types occupy well-defined regions and can be easily identified. About 10 000 asteroids were classified taxonomically using a probabilistic approach. The distribution of basaltic asteroids across the Main Belt was characterised using the MOVIS colours: 477 V-type candidates were found, of which 244 are outside the Vesta dynamical family.

Context

The total number of minor planets (small Solar System bodies orbiting the Sun) known today exceeds 700 000. The vast majority of them are concentrated between the orbits of Mars and Jupiter, in the asteroid Main Belt. These objects are the remnants of planetesimals from which the planets formed, and understanding their properties in detail allows the formation and evolution of the Solar System to be constrained. Other arguments for studying minor planets are related to more practical reasons: their use as resources for space exploration; and in order to mitigate the risk of impacts by near-Earth objects.

The physical properties of minor planets are known for just a small fraction of these objects: spectroscopic studies and light curves exist only for several thousand. The results show an unexpected diversity in the composition, density and shape of these bodies. The Sloan Digital Sky Survey (SDSS) and Wide-field Infrared Survey Explorer (WISE) provide information for about 100 000 minor planets. The resulting visible colours and albedos show a greater mixing of the bodies as a function of their orbital parameters, which can be explained by the turbulent history of the Solar System (DeMeo et al., 2015 and references therein). However, some of the most important spectral features used to reveal the compositions of minor planets are in the near-infrared region. A large survey with observations sampling this spectral region allows us to refine and complement the global picture of these bodies provided by SDSS and WISE data.

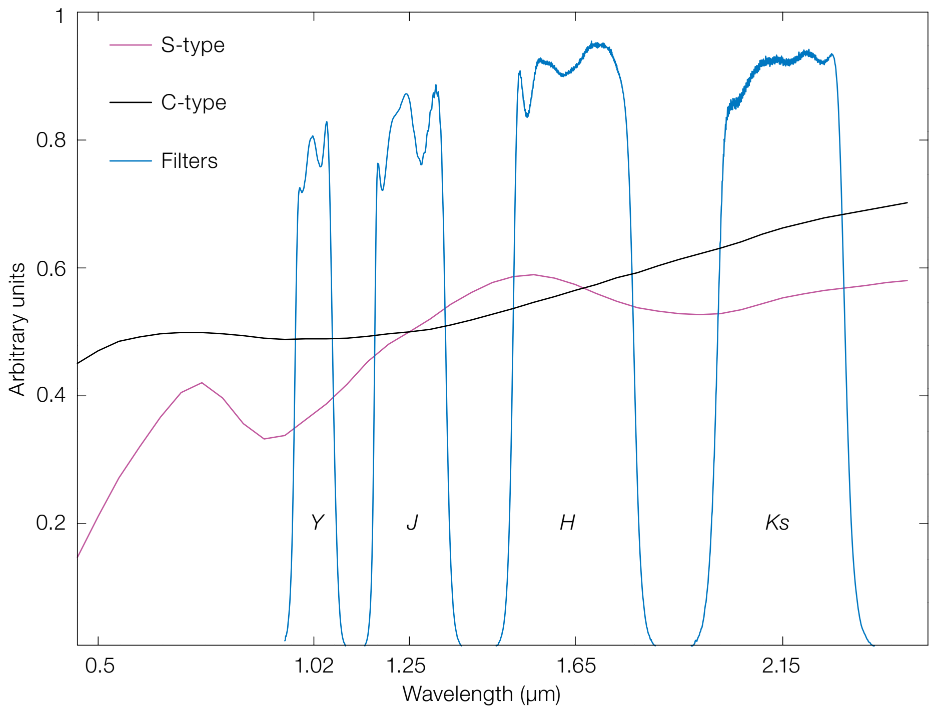

Figure 1. The normalised throughput profiles of the VISTA filter compared with two asteroid spectral types.

The survey conducted with the Visible and Infrared Survey Telescope for Astronomy (VISTA), the VISTA Hemisphere Survey (VHS[1]), provides such a survey for minor planets. VHS is the largest survey being conducted by the VISTA telescope. VHS images the entire southern hemisphere using four filters in the near-infrared region, namely *Y*, *J*, *H* and *Ks* (McMahon et al., 2013; Cross et al., 2012). The band centres of these filters are located at 1.02, 1.25, 1.65 and 2.15 μm respectively. Figure 1 shows the transmission curves of the VISTA filters compared to the spectra of two of the most typical asteroid classes, the primitive C-type and the rocky S-type. Notice that these four filters allow sampling of some of the main spectral features we expect for asteroids: the spectral slope and the two wide absorption bands at 1 and 2 μm, produced by minerals like olivine and pyroxene.

Detection of minor planets in VHS

With the aim of characterising the minor planet population in the VHS, we performed a serendipitous search within the observational products of the survey. In order to detect the minor planets, we used the fact that Solar System objects

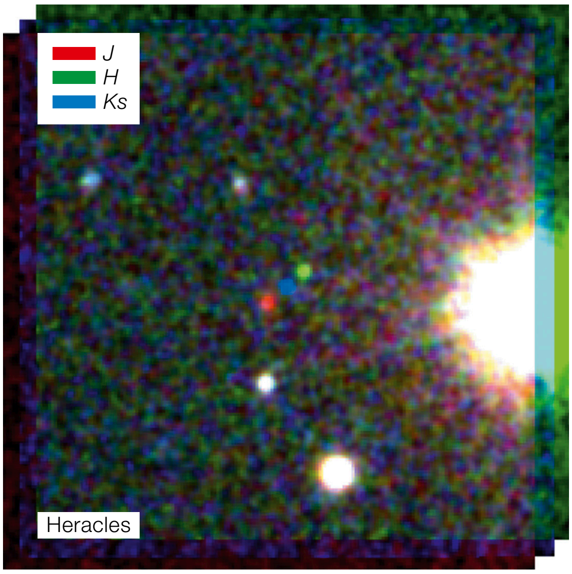

Figure 2. (Left) False-colour image obtained by combining the stack of frames observed with *J*, *H* and *Ks* filters on 5 November 2010. Owing to the differential motion of 0.24 arcseconds per minute, the asteroid (5143) Heracles appears as a different source in each filter.

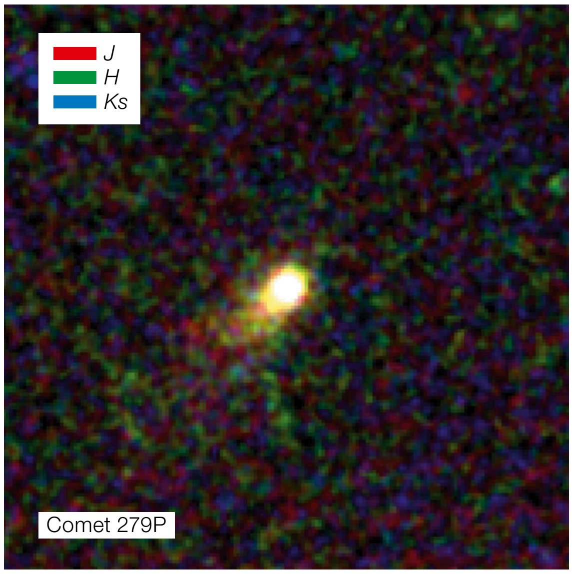

Figure 3. (Right) False-colour image obtained by combining the stack of frames observed with *J*, *H* and *Ks* filters for the comet 279P.

appear as moving sources compared with the background stars. This is exemplified in Figure 2, using a false-colour image obtained by combining the stack of frames observed with *J*-, *Ks*- and *H*-band filters on 5 November 2011 at 02:32, 02:42 and 02:52 UT, respectively. In this case, the near-Earth asteroid (5143) Heracles moved about 2.5 arcseconds between the three consecutive observations and hence appears as three separate images compared with the background stars.

Identifying the Solar System objects observed in a given field requires cross-matching of the detected coordinates with those computed at the moment of observation. A dedicated pipeline — called MOVIS (Moving Objects VISTA Survey) was designed for this task. The first step consists of predicting the position of Solar System objects potentially imaged in each field and retrieving the corresponding detections from the survey products. Secondly, MOVIS removes the mis-identifications based on an algorithm that takes into account the difference between the observed and the computed (O–C) positions and also by comparing with the PPXML star catalogue (of positions, proper motions, Two Micron All Sky Survey [2MASS] near-infrared and optical photometry). Finally, the information is provided in three catalogues for the purpose of organising the data for different types of analysis: MOVIS-D contains the parameters corresponding to all detections; MOVIS-M contains the magnitudes obtained with different filters for each object and selected by taking into account the timing constraints; and MOVIS-C lists the colours which are useful to infer the mineralogy.

The MOVIS catalogues are available online via the Centre de Données astronomiques de Strasbourg (CDS[2]) portal. The information provided includes observational details, and photometric and astrometric measurements. The astrometric positions, corresponding to 230 375 valid detections, were submitted to the International Astronomical Union Minor Planet Center[3], and all of them were validated. The observatory site received the code W91-VHS-VISTA.

The first published catalogues (Popescu et al., 2016a) used the VHS-DR3 data release, which contains the observations performed between 4 November 2009 and 20 October 2013. A total of 39 947 objects were detected, including 52 Near Earth Asteroids (NEAs), 325 Mars Crossers, 515 Hungaria asteroids, 38 428 Main Belt asteroids, 146 Cybele asteroids, 147 Hilda asteroids, 270 Trojans, 13 comets (see example in Figure 3), 12 Kuiper Belt objects and Neptune with its four satellites. About 10 000 objects have accurate spectro-photometric data (i.e., magnitude errors less than 0.1) allowing compositional information to be inferred (Popescu et al., 2016a).

The VHS-DR3 release covers ~ 40 % of the planned survey sky area; thus by the end of the survey the total number of Solar System objects observed will be at least double these numbers.

Near-infrared colours of minor planets

In order to derive compositional information for minor planets, it is necessary to correlate the spectral behaviour with the colours. This can be accomplished using the taxonomic classes of asteroid spectral data (since the large majority of the objects are asteroids). The main goal of taxonomies is to identify groups of asteroids that have similar surface compositions. The fact that spectra similar to the templates proposed by the taxonomic systems were systematically recovered by independent authors using diverse data sets and different methodologies provides confidence in these systems.

The first approach consisted of analysing the observed MOVIS-C colours for the objects already classified taxonomically. There are about 185 objects with spectra obtained by the Small Main-belt Asteroid Spectroscopic Survey (SMASS) and the S3OS2 visible spectroscopic survey of 820 asteroids. Within an error of ~ 5 %, the main compositional groups are completely

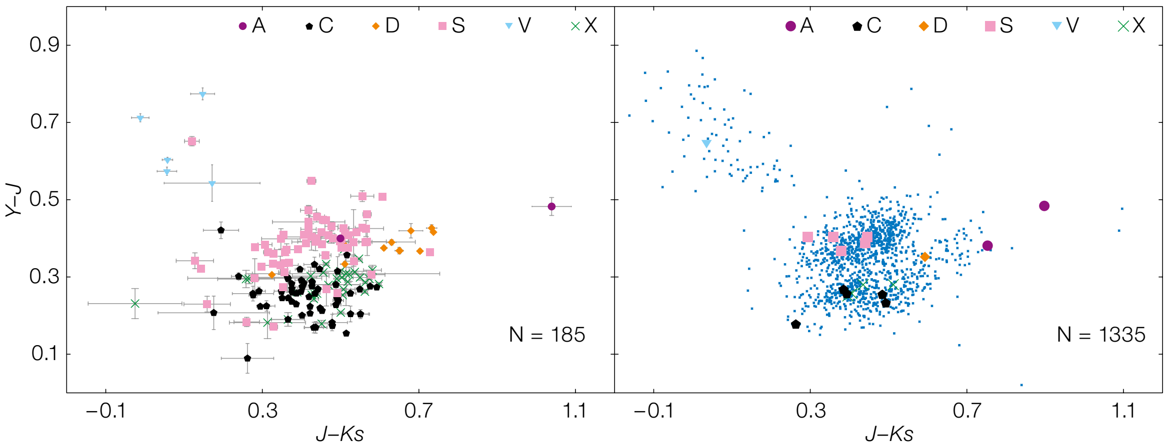

Figure 4. Left panel: the colours of asteroids with visible spectra, having an assigned taxonomic type. Right panel: the colours computed for the template spectra of the taxonomic classes from DeMeo et al. (2009) compared with the MOVIS-C data with colour errors less than 0.033 mag. From Popescu et al. (2016a).

separated (Figure 4) using the (*Y–J*) versus (*J–Ks*) colour-colour plot (Popescu et al., 2016a). This is the case for S-, C-, A-, D-, V- and C-type asteroids. S-type are objects with spectra similar to ordinary chondrite meteorites; C-type spectra are similar to carbonaceous chondrites; A-type are olivine-rich asteroids; D-type are objects with low albedo and a featureless red spectrum; V-type are asteroids with a basaltic composition, the most representative one being the asteroid (4) Vesta. The X-types present featureless spectra with a moderate slope and are representative of objects of different compositions: primitive, like carbonaceous chondrites; or metallic, like enstatite chondrites. Knowledge of the albedo is necessary to derive compositional information of an X-type asteroid.

The second approach is to compare the distribution of MOVIS-C data in colour-colour space with the position of colours computed for the template spectra of the different taxonomic classes spanning the visible to the near-infrared region (DeMeo et al., 2009).

In Popescu et al. (2016a) we show that the (*Y–J*) colour is a key parameter for a taxonomic classification: those with the 1 μm band have a large value of (*Y–J*) colour. The colour-colour plots which use the *Y* filter allow separation of the taxonomic classes much better than has previously been possible using other colours. Even for large photometric errors (up to 0.15 mag), the diagrams (*Y–J*) *vs* (*Y–Ks*) and (*Y–J*) vs (*J–Ks*) clearly separate the asteroids belonging to the main spectroscopic S- and C-complex, as well as the end taxonomic type members A-, D-, R-, and V-types (Popescu et al., 2016a). This survey thus provides an important tool for investigating the faint asteroids which are hard to observe spectroscopically.

Based on the available data we were able to classify about 10 000 objects using a probabilistic approach which takes into account the errors in the object photometry and the position of the class in colour space (Popescu et al., 2017). A further step is to integrate into this schema the photometric data obtained by SDSS and WISE.

A particular case: the basaltic asteroids

Basaltic asteroids are considered to be fragments of large bodies whose interiors reached the melting temperature of silicate rocks and subsequently differentiated (a core of heavy minerals is formed with a mantle of lighter minerals, such as olivine and pyroxene). These asteroids are classified as V-types and are identified by their spectrum in the 0.5–2.5 μm region which shows two deep and sharp absorption bands at 0.9 and 2 μm. Most of the objects with these characteristics orbit in the inner part of the Main Belt and are members of the Vesta collisional family, or are likely scattered members of this family. These objects are chunks of the crust of the asteroid (4) Vesta, ejected from it due to a collision. The presence of basaltic asteroids, unlikely to be scattered members of the Vesta family, clearly shows that there were other big differentiated basaltic asteroids in the Main Belt in the early age of the Solar System. This hypothesis challenges the models of the radial extent and the variability of the early Solar System temperature distribution, which generally do not predict melting temperatures in this region. V-type asteroids with orbits in the middle and outer part of the Main Belt are unlikely to be scattered Vesta family objects.

Near-infrared colours allow the easy identification of the V-type candidates: asteroids with (*Y–J*) > 0.5 and (*J–Ks*) > 0.3 mag are likely to be members of this class. Using the more accurate MOVIS-C data (with uncertainties < 0.1 mag), and the colour criteria described above, we have identified 477 objects, of which 244 of the V-type candidates are outside the Vesta dynamical family (Figure 5). This sample almost doubles the number of known V-types that are not members of the Vesta family (Licandro et al., 2016). In particular we identified 19 V-type asteroids beyond the 3:1 mean motion resonance, 13 of them in the middle part of the Main Belt and six in the outer part.

Acknowledgements

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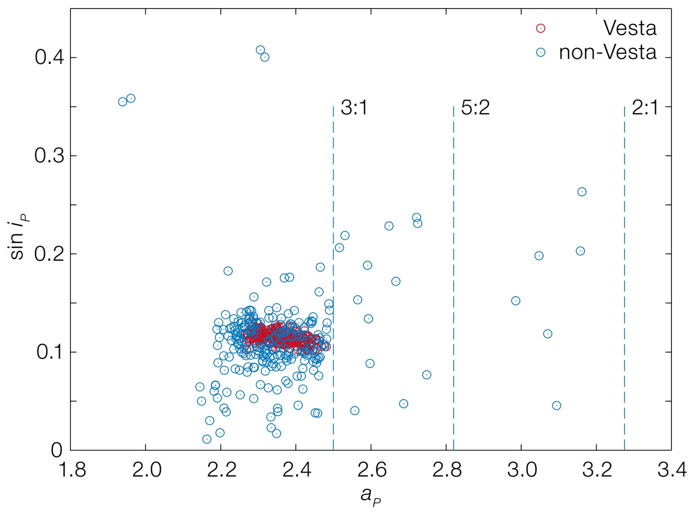

Figure 5. Distribution in proper orbital elements of the V-type candidates from the VHS survey. The figure shows the proper semi-major axis (a_p) *vs* the sine of the proper inclination (i_p). Red circles are Vesta family members, while blue circles indicate objects out of the Vesta family. The vertical dashed lines correspond to the most relevant mean motion resonances (Licandro et al., 2016).

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Links

[1] VHS: http://www.vista-vhs.org/
[2] CDS catalogues: http://cdsarc.u-strasbg.fr/viz-bin/Cat
[3] IAU Minor Planet Center: http://www.minorplanetcenter.net/iau/mpc.html
[4] http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=J/A%2BA/591/A115

R. Wesson/ESO

Composite image of sunset and star trails over the La Silla Observatory photographed from the 3.6-metre telescope with a series of long exposures. See Picture of the Week potw1647 for information.

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The Nearby Evolved Star L_2 Puppis as a Portrait of the Future Solar System

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The impact of the dramatic terminal phases of the lives of Sun-like stars on their orbiting planets is currently uncertain. Observations with NAOS CONICA and SPHERE/ZIMPOL in 2014–2015 have revealed that the nearby red giant star L_2 Puppis is surrounded by an almost edge-on disc of dust and gas. We have observed several remarkable features in L_2 Pup: plumes, spirals, and a secondary source (L_2 Pup B) which is embedded in the disc at a projected separation of 2 au. ALMA observations have allowed us to measure a mass of 0.659 ± 0.043 $M_\odot$ for the central star. This indicates that L_2 Pup is a close analogue of the future Sun at an age of 10 Gyr. We also estimate the mass of L_2 Pup B to be 12 ± 16 M_{Jup}, implying that it is likely a planet or a brown dwarf. L_2 Pup therefore offers us a remarkable preview of the distant future of our Solar System.

Five billion years from now, the Sun will grow into a red giant star, more than a hundred times larger than its current size. It will also experience intense mass loss in the form of a stellar wind. The end product of its evolution, seven billion years from now, will be a white dwarf star — about the size of the Earth and extremely dense (density ~ 5×10^6 g cm^{-3}).

This metamorphosis will have a dramatic impact on the planets of the Solar System, including the Earth. While Mercury and Venus will be engulfed by the giant star and destroyed, the fate of the Earth is still uncertain. The brightening of the Sun will make the Earth hostile to life in about one billion years. As an aside, assuming that life appeared on Earth 3.7 billion years ago (Ohtomo et al., 2014), this implies that life on Earth has already exhausted ~ 80 % of its development time. However, we do not know whether our then-lifeless rock will be destroyed by the burgeoning Sun, or survive in orbit around the white dwarf.

To address the question of the impact of the final phases of stellar evolution on planetary systems, hydrodynamical models have been proposed (see, for example, the recent review by Veras, 2016). But observational constraints on the star-planet interaction models are still rare. Planets of asymptotic giant branch (AGB) stars are embedded in complex circumstellar envelopes and are vastly outshone by their parent star. The observation of this critical phase of planetary system evolution thus presents considerable, and as yet unsolved, technical challenges. As a result, there currently exists only indirect evidence of the presence of planets orbiting AGB stars (Wiesemeyer et al., 2009). In addition, the masses of AGB stars are notoriously difficult to estimate from observations, preventing accurate determinations of their evolutionary states.

The discovery of the disc of L_2 Puppis with NACO

At a distance of only 64 pc (van Leeuwen, 2007), L_2 Pup is the second nearest AGB star after R Doradus. In addition to its regular pulsation with a period of 141 days and an amplitude of ~ 2 magnitudes in the visible, L_2 Pup has experienced a remarkable, slow photometric dimming over the last decades by more than 2 magnitudes in the visible. Bedding et al. (2002) interpreted this long-term dimming as the consequence of the obscuration of the star by circumstellar dust.

We observed L_2 Pup on the night of 21 March 2013 with NAOS CONICA (NACO) as part of a survey aimed at imaging the circumstellar environments of selected nearby evolved stars (Kervella et al., 2014a). We used 12 narrow-band filters spread in wavelength between 1.04 and 4.05 μm. We processed the image cubes using a serendipitous imaging approach (also known as "Lucky imaging"). Using 8400 very short exposures (8 milliseconds each) in each filter, we were able to freeze the residual atmospheric perturbations. After selecting the best 50 % of the series of images, we recentred and averaged them to obtain the 12 final, diffraction-limited images. They were finally deconvolved using a point spread function (PSF) calibrator star. The morphology of L_2 Pup in these images (Figure 1) was very surprising. From a seemingly double source between 1.0 and 1.3 μm, the star became a single source with an east-west extension at 2.1 μm, and exhibited a spectacular spiral loop at 4.0 μm!

We proposed (Kervella et al., 2014a) that L_2 Pup is surrounded by an equator-on dust disc. In this framework, the opacity and thermal emission of the dust change dramatically between 1 and 4 μm, providing a natural explanation for the changing aspect of the circumstellar envelope. At 1 μm, the dust efficiently scatters the light from the star, which therefore appears masked behind the dust band. The dust becomes progressively more transparent as the wavelength increases. At 2.2 μm, the thermal emission from the hot inner rim of the disc is observable through the dust. A colour composite image of L_2 Pup in the near infrared is presented in Figure 2. It shows the intrinsically red colour of the equatorial dust band due to the stronger scattering at shorter wavelengths.

Our hypothesis of an edge-on dust disc was initially relatively fragile. But a 3D

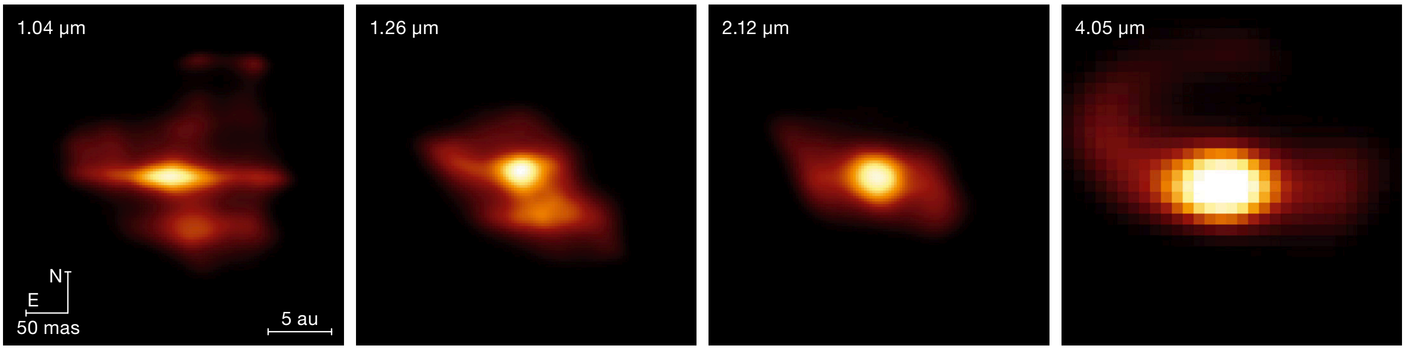

Figure 1. NACO deconvolved images of L_2 Puppis at a range of wavelengths from 1 to 4 μm. From Kervella et al. (2014a).

radiative transfer model using the RADMC-3D code (Dullemond, 2012) confirmed that this interpretation of the NACO images is consistent with the observations, reproducing convincingly both the spectral energy distribution and the morphology of the disc (Kervella et al., 2014a).

Stunning features from SPHERE polarimetric imaging

We took advantage of the Science Verification of the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) to observe L_2 Pup in visible light imaging polarimetry with the Zurich IMaging POLarimeter (ZIMPOL) camera (Kervella et al., 2015). The observation was carried out on the night of 7 December 2014. The combination of the high brightness of L_2 Pup and good seeing resulted in spectacular image quality. The Strehl ratio produced by the SPHERE adaptive optics reached more than 40 % at a wavelength of 646 nm for an atmospheric seeing of ~ 0.7 arcseconds. In one hour of telescope time, the observation of L_2 Pup and a PSF calibrator star (β Col) confirmed unambiguously our hypothesis of an edge-on circumstellar dust disc (Figure 3, upper left). In addition to revealing the overall geometry of the dust disc — as relatively thin, moderately flared and extending to at least 13 au — the collected images in the *V*- and *R*-bands showed remarkable structures in the envelope of L_2 Pup (Figure 3, upper right). We detect several spiral arms in the nebula, as well as two intriguing thin plumes. The central source appeared significantly elongated, and the subtraction of the central star revealed the presence of a second source, L_2 Pup B, at a separation of 32 milliarcseconds (mas) from the star to the west (Figure 3).

The polarimetric imaging capability of ZIMPOL has been particularly important in revealing the structure of the envelope of L_2 Pup (Figure 3, right). As the star is embedded in a dust-rich environment, the scattering of the starlight by the dust grains induces a linear polarisation of the photons. For small dust grains, the degree of linear polarisation p_L is a smooth function of the scattering angle, with a maximum p_L value obtained for ~ 90° scattering. Knowing the degree of polarisation therefore allowed us to estimate the scattering angle θ over the envelope. Knowing θ and the projected position of the dust relative to the star in the image, then allowed us to retrieve the 3D distribution of the scattering material. This polarimetric tomography technique was previously employed, for example, by Sparks et al. (2008) and Kervella et al. (2014b).

Apart from the scattered light on the disc's upper and lower surfaces, a very striking signature in the p_L map (Figure 3, right panel) comes from the two plumes emerging from the disc. Their high degree of polarisation (~ 30 %) indicates that they contain dust and that the scattering angle is large at $\theta \sim 50°$. These thin plumes, whose transverse diameter is smaller than 1 au, have a length of more than 10 au. The large scattering angle implies that they emerge from the disc close to perpendicular, and propagate in the northern cone cavity that is otherwise essentially devoid of dust.

The map of the degree of polarisation also shows well-defined local maxima at a radius of 6 au, symmetrically east and west of the star. The degree of polarisation reached at these positions is very high, up to p_L = 60 % in the *R*-band, corresponding to scattering of the light at

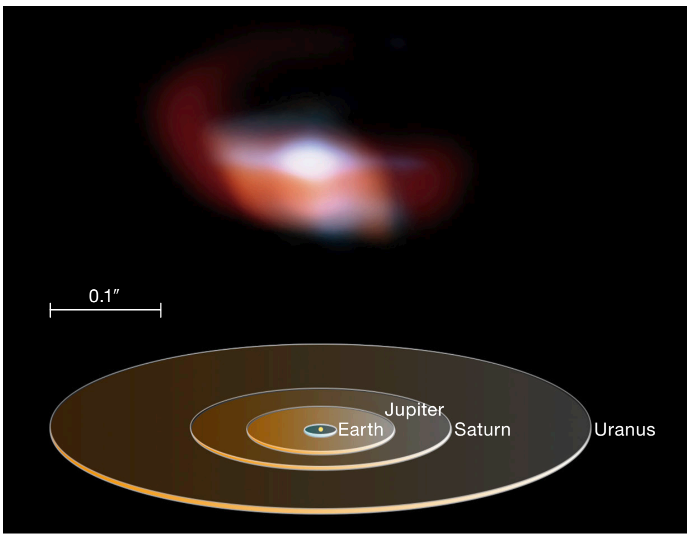

Figure 2. Colour composite image of L_2 Pup at infrared wavelengths assembled from NACO observations. The orbits of four Solar System planets are represented in the lower part of the figure to give the overall scale of the L_2 Pup disc.

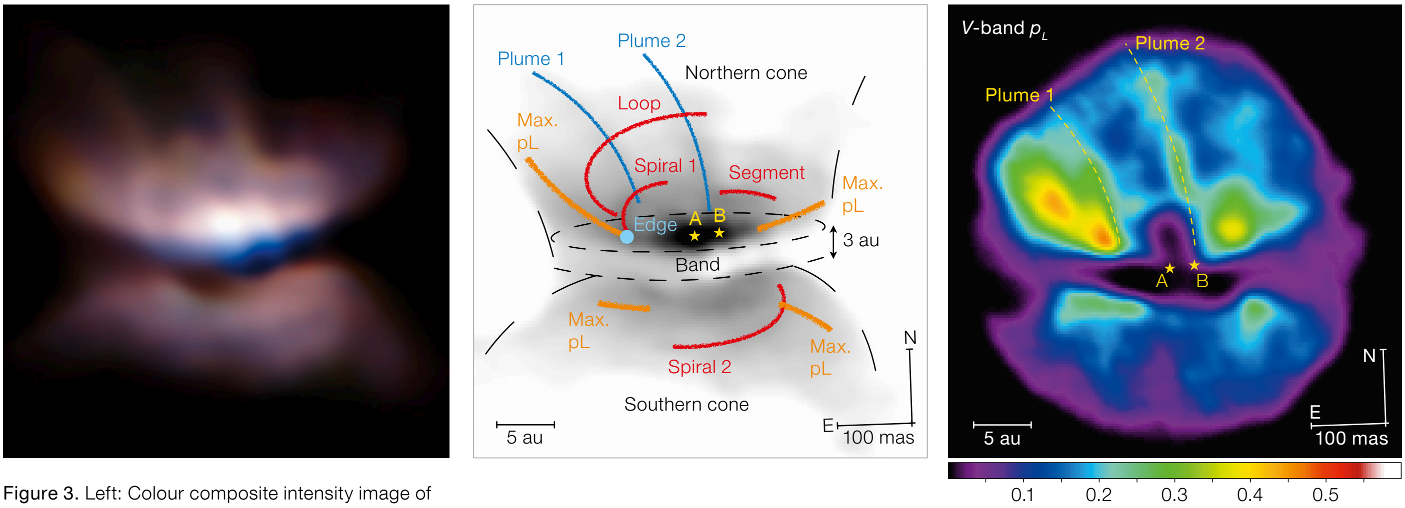

Figure 3. Left: Colour composite intensity image of L_2 Pup assembled from SPHERE/ZIMPOL *V*- and *R*-band images. Middle: nomenclature of the observed structures in the circumstellar environment of L_2 Pup. Right: degree of linear polarisation, p_L, of L_2 Pup measured with ZIMPOL. The two plumes sketched in the middle panel are also indicated.

~ 90°. We interpret these maxima as the scattering of the starlight by the inner rim of the dust disc, that is, the minimum radius at which the dust is present with a high density. The existence of an inner rim is due to the very high brightness of the central star (2000 times Solar luminosity), which would lead to the sublimation of any dust grains closer to the star (Homan et al., 2017).

An analogue of the future Sun, 5 billion years from now

L_2 Puppis was observed with the Atacama Large Millimeter/submillimeter Array (ALMA) in Cycle 3 in Band 7 (340 GHz, wavelength ~ 0.8 mm) using the longest available configuration of the interferometer with baseline lengths of up to 16 km (Kervella et al., 2016). This configuration provided the highest possible angular resolution currently achievable by ALMA, with a beam size of only 15 mas. It is interesting to remark that this resolution matches very well that of SPHERE/ZIMPOL in the visible (16–20 mas). We selected velocity resolutions of 100 to 400 m s^{-1} for the molecular line spectral windows, corresponding to a spectral resolution of R ~ 1 000 000. This powerful combination of very high spatial and spectral resolution is permitted by the high brightness of L_2 Pup and the high sensitivity of the array. We detected several molecular emission lines in the selected spectral windows, from ^{12}CO, ^{13}CO, H_2O, SO_2, ^{29}SiO, SiS and SO. We focus our discussion here on the $^{29}SiO(v = 0, J = 8\text{–}7)$ molecular line at a rest frequency of 342.981 GHz. The continuum subtracted integrated intensity in this line is presented in Figure 4 (upper left panel).

Our analysis is based on the position-velocity diagram (PVD) formalism. The PVD is computed by integrating the ALMA spectro-imaging data cube over a 0.02 arcsecond wide pseudo-slit aligned with the disc plane (east-west direction). The resulting diagram (Figure 4, lower left) shows the velocity of the molecular gas as a function of the position along the slit. Thanks to the excellent signal-to-noise ratio of the ALMA data, we can measure very accurately the orbital motion of the gas in the disc plane, and more precisely the maximum velocity of the gas as a function of the separation from the centre of rotation. We determined that this maximum velocity profile closely follows Kepler's law up to a radius of 5–6 au from the star. Figure 4 (lower left and right panels) clearly shows the two rotation regimes: Keplerian within the inner 5 au (that is, $v \sim R^{-1/2}$), and sub-Keplerian beyond 6 au ($v \sim R^{-0.85}$). A smooth transition is observed between 5 and 6 au. From the Keplerian motion of the inner 5 au, we could determine with very high accuracy (± 6.6 %) the present mass of the AGB star, finding that it is two-thirds the mass of our Sun (0.653 ± 0.043 $M_\odot$). It is remarkable that the error budget of this measurement is fully dominated by the uncertainty in the parallax of L_2 Pup, as the error from the ALMA data fit is only ± 1.7 %.

The coincidence of the radius where the rotation becomes sub-Keplerian and the radius of the inner rim (maximum of p_L, Figure 3) of the dust disc observed with ZIMPOL indicates that the rotation of the gas becomes sub-Keplerian precisely when it enters the dust disc. This very interesting effect is likely due to the viscous coupling of the gas and dust within the disc. The dust is sensitive to the strong radiative pressure from the central star, and is thus subject to a reduced effective gravity resulting in a slower orbital velocity than the gas. As the internal cavity within 5 au contains very little dust, the gas rotates freely there. But when it reaches the inner rim of the dust disc, it is slowed down by friction with the dust, which explains its sub-Keplerian rotation.

From the measured mass of L_2 Pup, stellar evolution models predict that its age is ~ 10 Gyr. The mass, radius and pulsation period are all consistent with a main sequence mass identical to that of the Sun. The missing third of a solar mass has been lost by L_2 Pup during its evolution. The extraordinary coincidence of having a Sun-like AGB star in the close vicinity of the Sun thus provides us with a privileged preview of the very distant future of our own star.

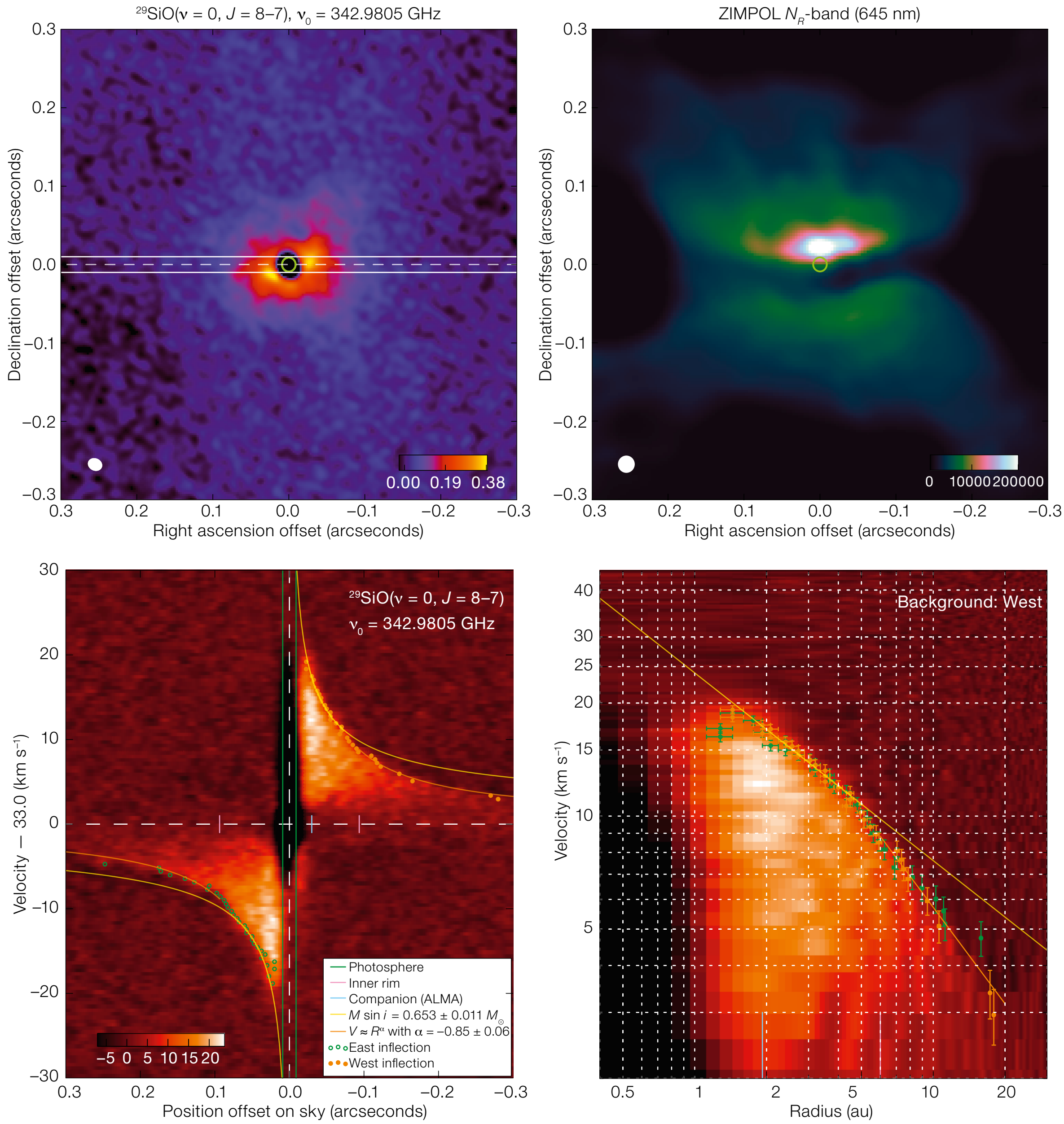

Figure 4. Upper left: ALMA integrated intensity image in the ^{29}SiO (ν = 0, J = 8–7) molecular line. The dark spot on the star is caused by gas absorption along the line of sight. Upper right: ZIMPOL image in R-band at the same scale. Lower left: Position-velocity diagram (PVD) constructed from the east-west pseudo-slit displayed in the upper left panel. Lower right: PVD in logarithmic velocity and radius scales to show the different power law regimes of the velocity profile. The domain and positions of various features are indicated according to the legend. The envelope of the maximum velocity profile defines the central star mass, and the inflection points corresponding to the inner edge of the dust disc are shown for the east and west edges.

A candidate planet orbiting in the disc of L_2 Pup

The ALMA data in the continuum showed the presence of an excess of emission in the western wing of the disc (Figure 5), contributing 1.3 % of the central star's flux. This emission coincides almost perfectly with the secondary source L_2 Pup B detected with SPHERE/ZIMPOL one year before the ALMA observations. This continuum emission could be produced by a dusty envelope or by an accretion disc surrounding L_2 Pup B.

We estimated the mass of the companion by comparing the position of the centre of rotation of the molecular disc and the position of the continuum emission peak. The centre of rotation of the molecular disc is very well defined from the ALMA PVD (Figure 4), and it corresponds to the centre of gravity of the mass enclosed by the disc. The continuum emission peak provides the position of the AGB star. We determined that the two points are coincident within 0.55 ± 0.75 mas. As we know the mass of the central star and the current separation of L_2 Pup B, we can convert this offset into a mass of 12 ± 16 M_{Jup} for this companion, which corresponds to a planet or a low mass brown dwarf.

We also detected excess emission in the PVD of the molecular lines (ν = 0, J = 3–2) of ^{12}CO and ^{13}CO at the location of the candidate planet, at a velocity of 12 km s^{-1} (Figure 6). We propose that this emission comes from the extended molecular envelope accreted by L_2 Pup B from the wind of the AGB star. This measured velocity is consistent with the line-of-sight projection of the velocity vector of a planet in circular Keplerian revolution at a radius of 2.4 au from a 0.65 $M_\odot$ central star, that is, with an orbital period of 5 years.

This candidate planet is, to our knowledge, the first planet whose emission is detected with ALMA. We also observe a signature at 6 au in the PVD that may be linked to the plume #1 detected in the ZIMPOL images (yellow arrow in Figure 6).

The persistence of L_2 Pup B between the ZIMPOL and ALMA observations is an indication that this is a compact object rather than a coreless aggregate of gas and dust. The strong Keplerian shear and the radiation pressure would very quickly blow such a clump into the dust disc (R > 6 au). Moreover, the presence of a plume originating from the position of L_2 Pup B and launched perpendicular to the dust disc plane is an indication that accretion is occurring. Such a possibility is plausible, as the Roche lobe of a planet embedded in the dust- and gas-rich environment surrounding L_2 Pup will sweep up a considerable volume and therefore accrete a significant quantity of material.

The presence of a candidate planet orbiting L_2 Pup provides a remarkable test case to observe the interactions between the evolved star's wind and a low-mass companion. Figure 7 shows our hypothesised structure of the detected features in the L_2 Pup system. We propose that the large dust loop observed at 4 µm in the NACO images is created by dust condensation in the shadow of L_2 Pup B. The highly collimated plume is ejected from a putative accretion disc surrounding the planet.

Compared to other AGB stars observed at high angular resolution, the morphology of the circumstellar disc of L_2 Pup stands out as remarkably singular. R Dor (Khouri et al., 2016) and W Hya (Ohnaka et al., 2016), although they are at a comparable stage of their evolution to L_2 Pup, do not host axially symmetric circumstellar structures but irregular, mostly spherical envelopes. We suggest that the axial geometry of the envelope of L_2 Pup is due to the presence of its companion. Its biconical shape is also strongly evocative of the bipolar planetary nebulae, and L_2 Pup may hold the key to demonstrating the link between binarity (including sub-stellar companions) and bipolarity of planetary nebulae.

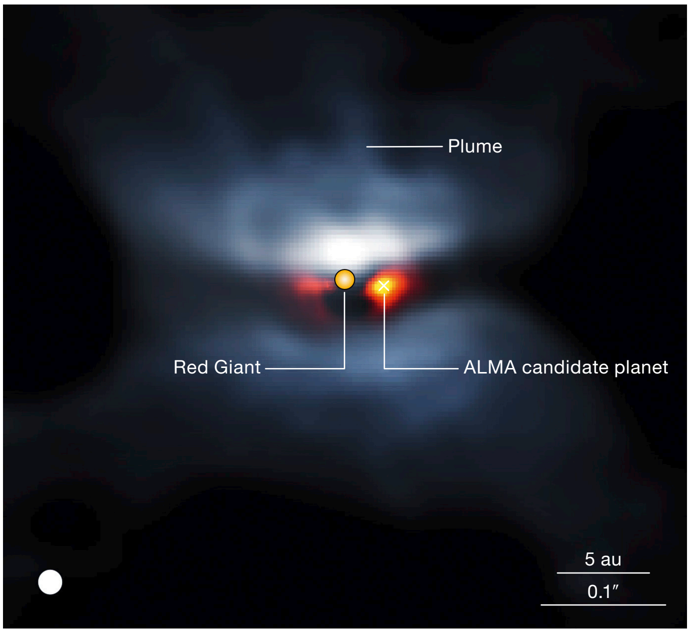

Figure 5. Composite view of L_2 Pup in visible light (ZIMPOL image in the R-band, blue colours) and ALMA continuum (orange colours). The central star light has been subtracted from the ALMA image to better show the companion object. The size of the star's photosphere is represented to scale. The white circle in the bottom left corner represents the resolution of the image (beam size).

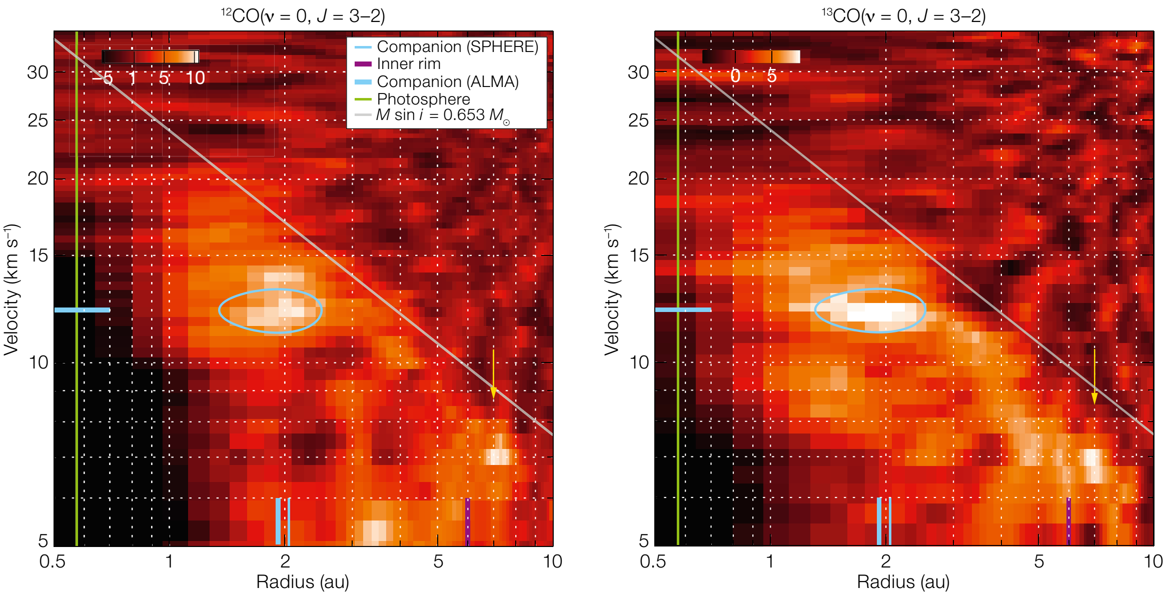

Figure 6. Emission of L_2 Pup B in two CO molecular isotopologue lines (^{12}CO to the left and ^{13}CO to the right) in position-velocity diagrams with logarithmic velocity and radius scales. The emission from the east wing of the disc has been subtracted. The positions of various key features are indicated in the legend, cf. Figure 4. The yellow arrow marks a feature tentatively ascribed to the Plume 1 (cf., Figure 3).

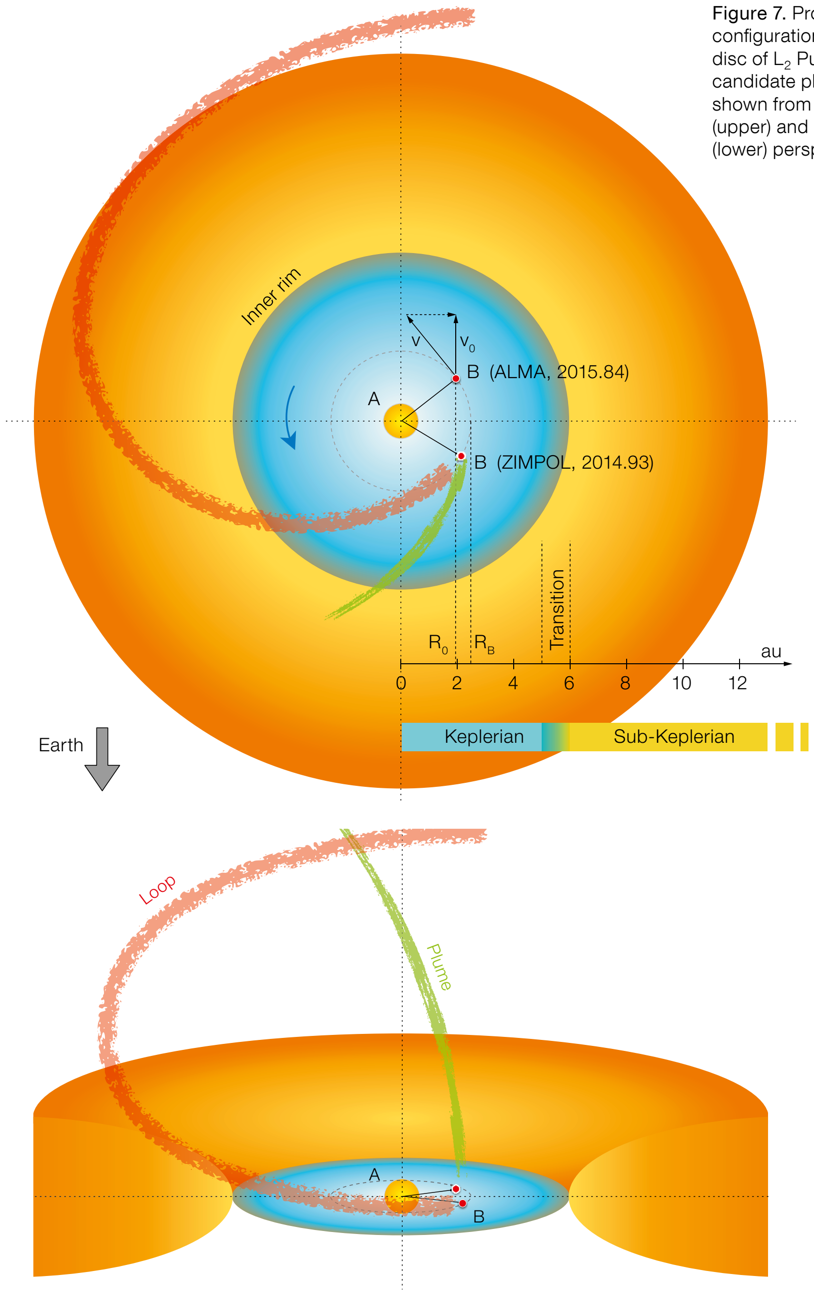

Figure 7. Proposed configuration of the dust disc of L_2 Pup and its candidate planet is shown from a pole-on (upper) and equator-on (lower) perspective.

Prospects for future observations

The longest ALMA baselines of 16 km combined with the shortest wavelengths (Bands 9 and 10) will soon give access to an angular resolution ~ 6 mas. Assuming a mass of 12 M_{Jup} for L_2 Pup B, its Roche lobe has a diameter of about 0.6 au, or 10 mas. This means that it will be possible to resolve the putative accretion disc around L_2 Pup B (particularly in CO molecular emission) and directly determine its mass from its Keplerian velocity amplitude.

Optical interferometry with the Very Large Telescope Interferometer (VLTI) commissioning instrument VINCI has been used by Kervella et al. (2014a) to measure the angular diameter of the central AGB star of L_2 Pup. The VLTI second-generation instruments GRAVITY (Eisenhauer et al., 2011) and the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE: Lopez et al., 2014; Millour et al., 2016) will enable milliarcsecond spectro-imaging of the photosphere and structures present around the star (plumes, loop, companion). We plan to develop the observations of L_2 Pup with these new instruments to monitor its pulsation cycle and its close-in molecular envelope (the molsphere, located within 1–3 stellar radii). The interaction of the molsphere with the orbiting planet L_2 Pup B may be an important ingredient in the accretion of gas.

The forthcoming Extremely Large Telescope (ELT) will provide an angular resolution of 60 mas at 10 µm, 12 mas at 2.2 µm and 3 mas in the visible. Observing L_2 Pup with the ELT will be easy: it is very bright (m_V ~ 7.5, m_K ~ −2), and thus provides an excellent natural guide star for adaptive optics wavefront sensing. With its 0.4 arcsecond extension, the circumstellar disc is easily resolved spatially, and high-resolution spectroscopy will provide a Doppler map of the molecular envelope. The interactions of the candidate planet with the dust disc and the wind of the central star will thus be observable in very fine detail, revealing the accretion of a stellar wind onto a planetary-mass object.

As an older sibling of our Sun, and thanks to the powerful existing and foreseen high angular resolution instrumentation available at the VLT and ALMA, L_2 Pup will undoubtedly continue to surprise us in the coming years with key discoveries pertinent to the distant future of the Solar System.

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Supernova 1987A at 30

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Thirty years on, SN 1987A continues to develop and, over the last decade in particular, has: revealed the presence of a large centrally concentrated reservoir of dust; shown the presence of molecular species within the ejecta; expanded such that the ejecta structure is angularly resolved; begun the destruction of the circumstellar ring and transitioned to being dominated by energy sources external to the ejecta. We are participating in a live experiment in the creation of a supernova remnant and here the recent progress is briefly overviewed. Exciting developments can be expected as the ejecta and the reverse shock continue their interaction, the X-rays penetrate into the cold molecular core and we observe the return of the material into the interstellar medium. We anticipate that the nature of the remnant of the leptonisation event in the centre will also be revealed.

In the preface to the first SN 1987A conference thirty years ago (Danziger, 1987), Lodewijk Woltjer, then Director General of ESO, welcomed the participants with the prescient statement "It is very well possible that […] SN 1987A will remain observable for thousands of years to come."

Introduction

If an observational astronomer was allowed to pick the parameters of the object of study, then ideally the angular size would be matched to the resolution of the telescope, the dimensions of the physical processes would be matched to the angular size and the variability matched to the proposal cycles for telescope time. If, in addition, the physics ranged across astroparticles and all wavelengths of the electromagnetic spectrum, then one might consider one had found the perfect source.

SN 1987A is just such a heavenly object! That it is circumpolar for the more southern astronomical sites adds to its optimality. Located in the Large Magellanic Cloud (LMC), it is near enough to be resolved, yet far enough to not be a threat, along an almost unextinguished line of sight, in a relatively uncluttered part of its host galaxy. It is evolving on a human timescale. Many articles on 1987A have appeared in the pages of The Messenger over the years and therefore we will not dwell here on the past but rather focus on the current state and ponder an exciting future. A comprehensive review (McCray & Fransson, 2016) appeared recently and covers SN 1987A over the past 10 000 days.

Despite fading by seven orders of magnitude from its peak, the supernova and its surroundings remain readily observable. Lengthy exposure times are still necessary to study the details and, critically, the timescales over which the supernova changes remain of order half a year (approximately the light travel time of the ejecta at this epoch); therefore continued vigilance is needed. ESO, together with the Hubble Space Telescope (HST) and the Australia Telescope Compact Array (ATCA), are the sole observatories that, thanks to the evolution of their observing capabilities, have provided the necessary continuous ultraviolet/optical/near-infrared/radio coverage of the supernova, and fortunately the fireworks are still continuing. Together with similar monitoring by the Chandra and X-ray Multi-Mirror Mission (XMM-Newton) space telescopes in X-rays, these facilities have provided a nearly complete multi-wavelength coverage of the development of the supernova. These telescopes are providing a legacy dataset for this object that cannot be repeated.

The progenitor star (Sanduleak −69°202) of SN 1987A cleared a volume around itself, sweeping-up material blown off in earlier evolutionary stages (about 8000 years ago) into an hour-glass structure dominated by an equatorial ring. This structure, first observed with the New Technology Telescope (NTT) in 1989, and made famous by HST, Chandra and ATCA images (see Figure 1, left), is readily visible in images from NAOS-CONICA (NACO), and the Spectrograph for INtegral Field Observations in the Near-Infrared (SINFONI) as well (Larsson et al., 2016). Figure 1 right shows a very recent NACO image at 2.15 μm (*Ks*-band). The flux in the *Ks*-band is dominated by Brackett-γ emission at 2.165 μm illuminated from the outside. The illumination of the ring at the earliest times, by the ultraviolet (UV) light emerging as the shock broke the surface of the progenitor star, was used to determine a geometric distance to the LMC and remains one of the anchors of the extra-galactic distance ladder. The ring illumination also provided the first evidence of the radiation from the shock break-out, lasting only a few minutes but with a temperature of about a million degrees.

Later, when the fastest ejecta, moving at ~10 % of the speed of light, reached the ring, the shocked gas emitted brightly at wavelengths from radio to X-ray. Recently, observations from HST have been used to show that the ring is beginning to suffer from the effects of the ejecta colliding into it (Fransson et al., 2015). It will take a while, but the ring is currently being destroyed. A simple extrapolation estimates this process will be complete by ~2025. However, new spots of emission outside the ring have appeared and continued observations may yet provide surprises about the surrounding structure. We get to watch in real time as a shock wave with well-defined characteristics impinges on a well-understood structure (both in density and composition); a text book illustration of shock theory.

Radioactivities

Inside the ejecta, radioactive species freshly synthesised in the explosion provide gamma rays and energetic positrons that deposit their energy into the ejecta, provided they do not escape. Which isotopes are present, and how much of each, are critical to our understanding of the emerging spectrum. The isotope mix also places limits on the mass cut (the mass coordinate in the proto-neutron star where the ejection starts and the collapse ends) and provides a measure of the

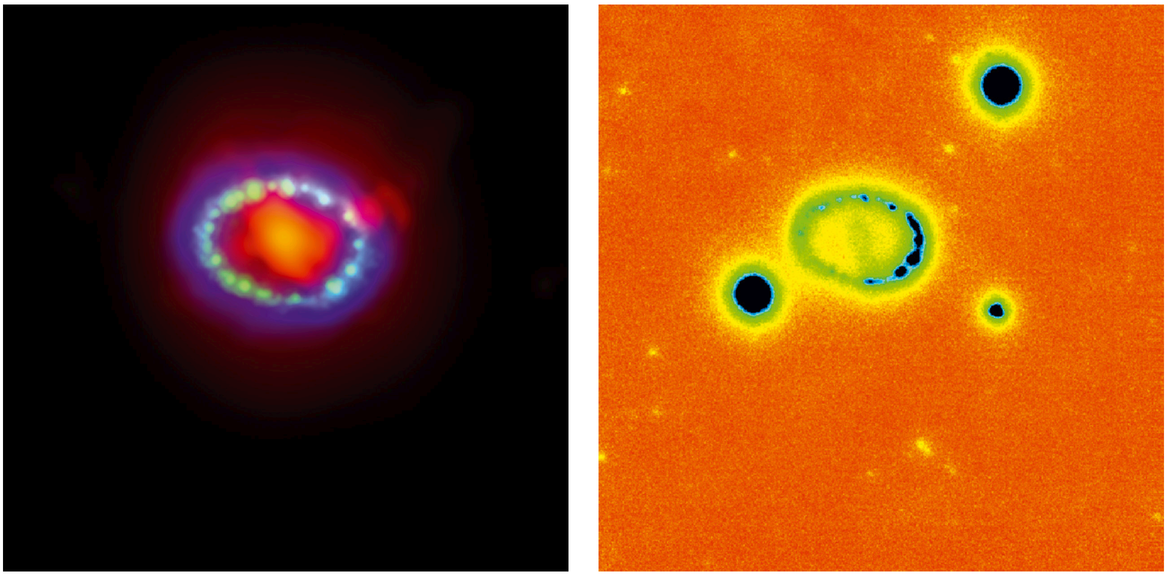

Figure 1. Left: combined HST (green), Chandra (blue) and ALMA (red) image of SN 1987A. Right: NACO data taken in January 2017 in the *Ks*-band. The ejecta emission in the centre of the ring is well resolved in both images; the short axis of the ring projects to 1 arcsecond on the sky. The west side of the ring can now be seen to be significantly brighter than the east side.

nucleosynthetic yield of the supernova. The presence of ^{56}Ni (source of ^{56}Fe) had long been confirmed in SN 1987A, as had ^{57}Co. Theory predicted that ^{44}Ti should also be made in the explosion of supernovae. Combining Very Large Telescope (VLT) and HST spectra with time-dependent non-local thermodynamic equilibrium (LTE) radiative transfer calculations, it was determined that ^{44}Ti had taken the role of key energy supplier to the supernova eight years after the explosion (Jerkstrand et al., 2011).

It was consequently exciting to see both the Nuclear Spectroscopic Telescope ARray (NuSTAR) detection (Boggs et al., 2015) and the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) detection by Grebenev et al. (2012) of hard X-ray lines from ^{44}Ti. Observations with SINFONI (Kjaer et al., 2010; Larsson et al., 2016) and HST (Larsson et al., 2011) have revealed a complex structure of emission from atomic species that, in some cases, are collocated with the radioactive species and in others are illuminated by external sources. In particular, the SINFONI observation of the 1.644 μm [Si I] + [Fe II] line gives a three-dimensional view of the ^{44}Ti distribution in the ejecta, responsible for powering the inner core. This distribution is one of the main diagnostics of the explosion dynamics during the first seconds.

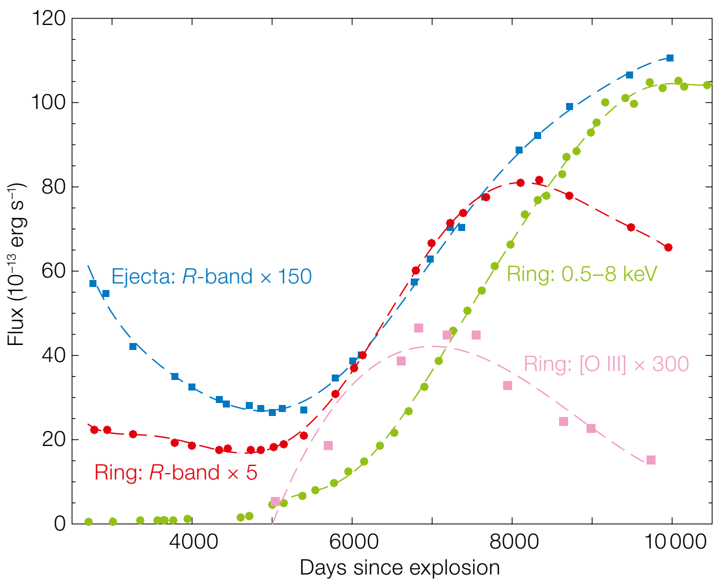

Figure 2. The light curve of the supernova over the past 5000 days. Different components and wavelengths are identified. The dimming of the ring in optical emission and the brightening of the emission from the ejecta, consequent on the input of energy from the reverse shock, are evident.

Shocks

While the forward shock moves through the ring, slowing down the ejecta and accelerating the ring material, the reverse shock is formed by the supernova ejecta hitting the decelerated medium behind the forward shock. The reverse shock is formed in successfully slower and denser regions in the supernova ejecta.

The supernova ejecta are being exposed from the outside to X-rays from the ring interaction and at some point during the supernova's teenage years the dominant source of energy became the conversion of kinetic energy from the supernova ejecta with the surroundings. Quite elegantly, just as the radioactive elements whose decay had powered the emission of the junior supernova exponentially decreased, the X-rays from the interaction with the inner ring provided the energy for an outside-in look at the ejecta. These X-rays are mainly absorbed in the hydrogen rich envelope and the metal core is still powered by decay of ^{44}Ti.

The different emission sites (ionised but unshocked ring material, shocked ring gas, reverse shock, inner supernova ejecta) account for the vastly different velocities, and are easily separated in the

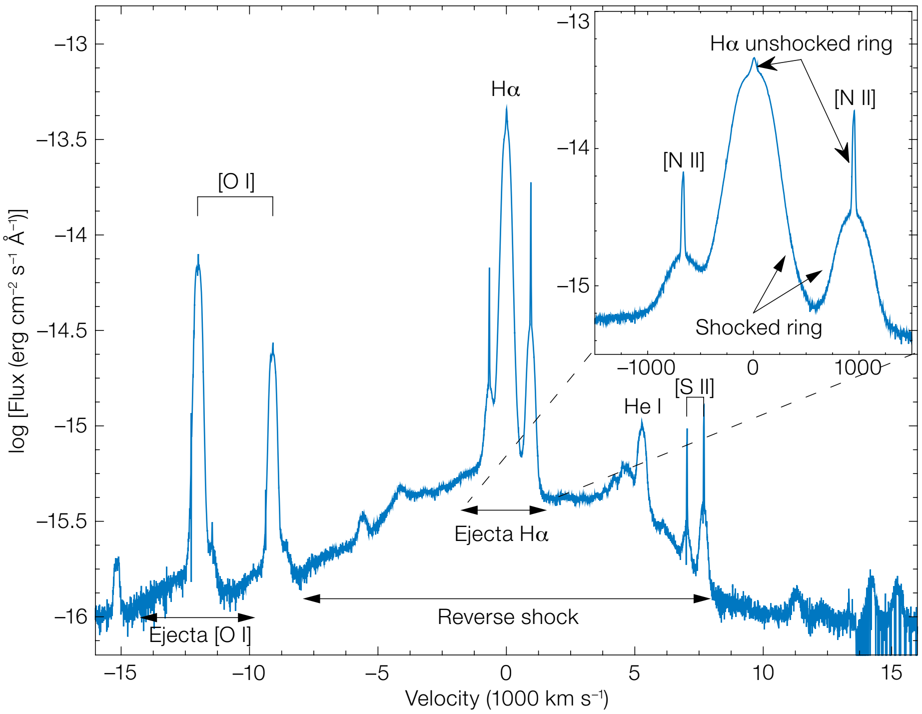

Figure 3. The UVES spectrum of SN 1987A around the Hα line in different zooms; spectrum taken in January 2012. The UVES slit covers the whole supernova, sampling the emission from all components; see text for details.

optical and infrared spectrum of the supernova. The UV-Visual Echelle Spectrograph (UVES) spectroscopy complements the HST imaging by providing separation of the different velocity components, and is perfectly suited both in wavelength coverage and resolution (see Figure 4 for the different velocity components in the Hα region). Spectra such as this have allowed us to follow the evolution of both the ring and ejecta emission continuously.

The dominant feature of the velocity profile from the whole supernova shown in Figure 4 is the ~500 km s^{-1} emission from the shocked ring, seen in Hα and the [N II] lines either side of it. The narrow feature on top of the broader profile is emission from the ionised ring gas at the systemic velocity of the supernova, +287 km s^{-1}. Over a range of 10 000 km s^{-1} and at a flux level less than 1 % of the peak of the ring emission, we see a strong box-like emission of Hα. This is emission from the supernova ejecta passing through the reverse shock. The emission from the inner core can be seen as the rising blue emission for velocities less than about 2500 km s^{-1}.

The ejecta continue to be observed across the optical and near-infrared spectral region. SINFONI with adaptive optics has been critical in providing a view of the near-infrared emission at a spatial resolution comparable to that of HST. This work has established the geometry of the emission in the lower ionisation lines of [Fe II] and [Si I]. These "core" elements play a critical role in cooling the ejecta while at the same time tracing the radioactive energy deposition. However, the SINFONI data also provided us with the ability to find previously undetected molecular gas.

Before construction of the VLT had even been approved, the discovery of hot (2000 K) molecular emission (CO and SiO) from within the ejecta of 1987A initiated the discussion of supernova chemistry. Chemical models also predicted formation of molecular hydrogen (Culhane & McCray, 1995). H_2 is notoriously shy and challenging to detect in the part of the spectrum approaching the thermal infrared, and therefore it was a pleasant confirmation to detect the emission (Fransson et al., 2016) in SINFONI data some 20 years after the explosion. Except for its very presence, the fact that the observed distribution reaches almost to the centre means that hydrogen was mixed by the Rayleigh-Taylor instabilities shortly after the explosion, as predicted by explosion models (for example, Wongwathanarat et al., 2015).

Dust and molecules

As new facilities come online, SN 1987A is not only a natural target but also a

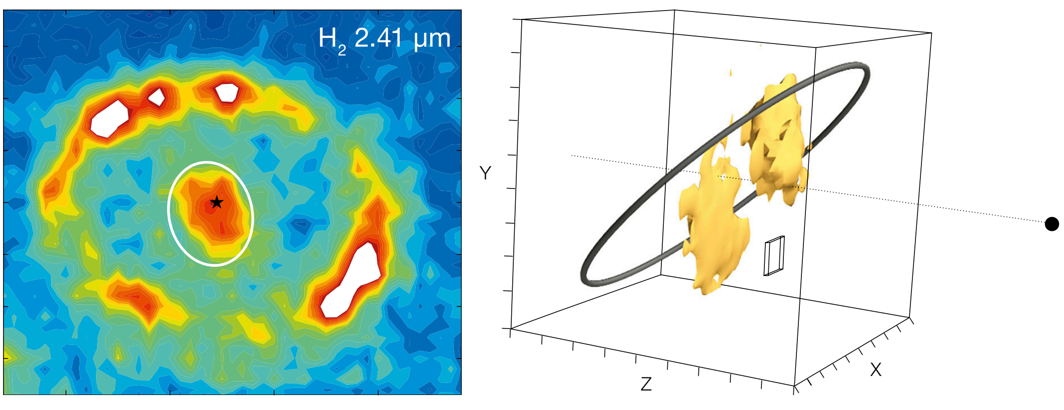

Figure 4. Left: SINFONI spectral image in the molecular hydrogen line at 2.40 μm (from Fransson et al., 2016). The bright ring is the continuum emission from the shocks and is not related to the molecular hydrogen in the inner ejecta. Right: 3D distribution of the 1.64 μm [Si I] + [Fe II] line from SINFONI. The ring is shown for reference and the tick marks on the box are at steps of 1000 km s^{-1}.

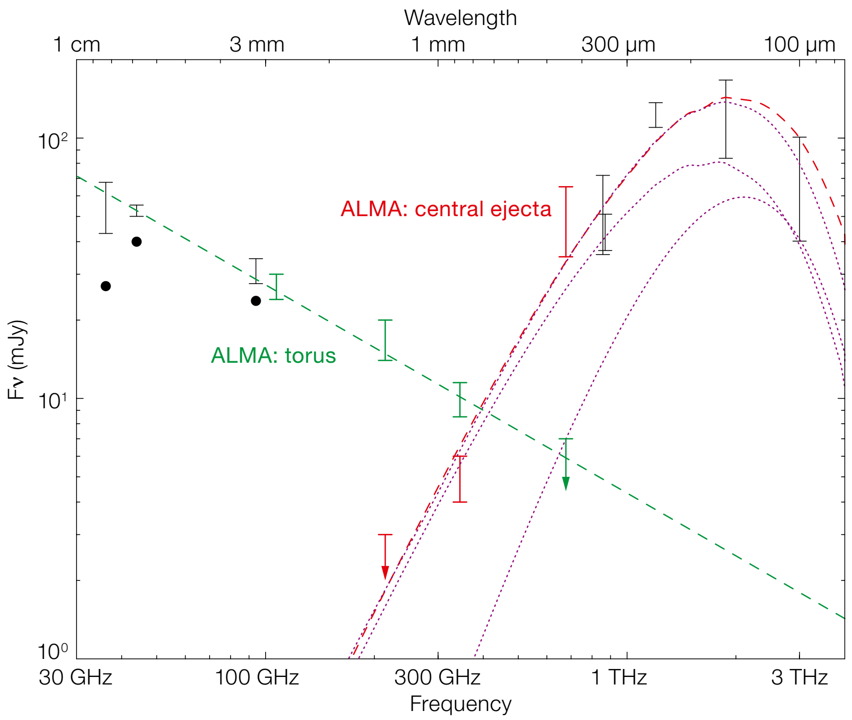

Figure 5. ALMA's angular resolution permits the separation of the continuum dust emission from the synchrotron power law radiation resulting from shocks in the ring. The measurements shortward of 400 μm are from Herschel (Matsuura et al., 2011) and APEX (Lakicevic et al., 2012) At low frequencies data come from ATCA (Potter et al., 2009; Zanardo et al., 2014). From Indebetouw et al. (2014).

source of new understanding. The Spitzer Space Telescope observed the supernova out to 30 μm and detected the presence of warm dust. Observations with the Gemini South telescope and the VLT in the 10 μm band showed that the thermal infrared emission comes from the equatorial ring. In 2010 the Herschel satellite observed the supernova in the far infrared and detected an enormous excess of emission longward of 100 μm (Matsuura et al., 2011). Contemporaneously, Lakićević et al. (2012) used APEX to detect emission from the supernova at 300 and 870 μm. Combining the flux with models of dust, Matsuura et al. (2011) concluded that between 0.1 and 1 $M_\odot$ of dust formed in the supernova.

Given the angular resolution of Spitzer and Herschel, the location of the cold dust remained uncertain. Observations in 2013 with ALMA at 1 mm and 450 μm at an angular resolution of ~ 0.5 arcseconds proved the unambiguous association of the cold dust with the inner ejecta of 1987A (Indebetouw et al., 2014; see Figure 5). The mass of the dust, however, remains "stubbornly high", above 0.5 $M_\odot$ (Matsuura et al., 2015). If the dust survives travelling through the reverse shock, then core-collapse supernovae may be a significant contributor to the dust budget in the early Universe.

The ALMA spectra provided further excitement in that, in addition to the dust observations, they revealed strong emission from CO 2–1 and SiO 5–4 transitions. Combined with a detection by Herschel of the CO 6–5 and 7–6 transitions, the temperature and mass determination could be refined by Kamenetzky et al. (2013). Approximately 0.01 $M_\odot$ of CO emits at a temperature of ~ 20 K and at an expansion velocity of 2000 km s^{-1}. It remains to be seen whether this is the same CO that was detected at 2000 K and 2000 km s^{-1} during the supernova's first year or represents new formation.

Fascinating new ALMA observations at high angular resolution are in the process of being published (Abellan et al., 2017, submitted). The cold CO and SiO in the centre of the supernova are seen to be separated into clumps. These are unique observations of the birth of a supernova remnant before the reverse shock disturbs the environment. We will need to remain vigilant to see whether the dust and molecules survive or are destroyed. Supernovae are certain to be prolific polluters of the early Universe in metals. Whether they also contribute dust and molecules to the mix, we will see in the experiment taking place before our telescopes.

The future

What can we expect for the future? The holy grail is certainly the nature of the compact object in the centre. The length of the neutrino burst indicated the formation of a neutron star, but with later fallback it is also possible that a black hole could have been formed. ATCA has been giving us a detailed view of the material around the supernova (Potter et al., 2009) and combining these radio data with ALMA mm/sub-mm data provides an interesting constraint set for the presence of a plerion, a region ionised by the strong magnetic field of the neutron star, in the centre of the remnant (Zanardo et al., 2014). Higher angular resolution observations with ALMA will help greatly.

From X-ray observations there is a strong upper limit to the luminosity in the 3–10 keV band of 3×10^{33} erg s^{-1} (Frank et al., 2016). The absorption of the X-rays by the ejecta may, however, still be large (Fransson & Chevalier, 1987; Orlando et al., 2015), although this decreases rapidly with the expansion of the ejecta. The clumpiness of the ejecta, as revealed by SINFONI and ALMA, is the main uncertainty. The optical/infrared may also provide an interesting window, since any absorbed X-rays may be reprocessed into this wavelength range. The infrared sensitivity of the James Webb Space Telescope (JWST) and the superior spatial resolution of the Extremely Large Telescope (ELT), will be especially exciting here. With the new and old facilities, we will, hopefully, during the coming decade reveal whether the leptonisation event that was responsible for the neutrinos ended in a neutron star or a black hole.

As for the ejecta and circumstellar medium, we are already seeing the decaying ring emission. The shock wave, however, continues out into the circumstellar medium beyond the ring, and will hopefully reveal more of the several solar masses of material thought to have been lost by the progenitor star. The mass of the ring is only ~ 0.06 $M_{\odot}$. The X-ray emission is expected to decay more slowly than the optical ring emission. It will therefore continue to illuminate more and more of the ejecta, and thus also give a new view of the abundance and hydrodynamic structure of the ejecta. The supernova will then gradually transform into a supernova remnant similar to other young remnants. We can follow this in real time for hundreds of years, perhaps longer, as suggested by Lo Woltjer. In all these aspects ESO can continue to play a leading role.

Ten years ago we were already musing about the future development of SN 1987A (Fransson et al., 2007). We predicted exciting events — the destruction of the inner ring and the illumination of material outside the ring. We were also hoping to find the compact remnant inside SN 1987A and hopefully other surprises. The ring has started to fade, indicating that it will be destroyed in the near future, and the first traces of material beyond the ring have also been found. The neutron star has so far defied detection.

There have indeed also been great surprises. Tracing the explosion mechanism by directly observing the geometry of the element distribution in the inner ejecta confirms the non-spherical explosion models. The illumination of the inner ejecta by X-rays from the ring is a new feature in the development of SN 1987A. It provides a novel and unexpected window on parts of the ejecta that have so far been unobservable. The molecules in the inner ejecta were predicted early on and have finally been found. ALMA, with its first observations, together with Spitzer and Herschel, have told us more about the dust in SN 1987A than we could have guessed two decades ago. The reverse shock has been firmly observed and adds another important aspect to the evolution of the supernova.

Acknowledgements

It is a pleasure to thank all the staff at the various observatories and in particular those involved in the Paranal and ALMA operations, both in preparing the observations in Garching and in executing them on the sites. They have all contributed through their expertise and enthusiasm to generating this beautiful and unique data set. We also want to thank the time allocation committees over the decades who have recognised the uniqueness of the supernova and have supported this research.

The authors thank the current editor, himself a naked eye observer of SN 1987A, for improving the article and wish the next editor a Galactic supernova for herself.

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A wide-field image (about 4 degrees in extent) of the Large Magellanic Cloud and 30 Doradus taken by the ESO 1-metre Schmidt telescope in 1986, before the appearance of SN 1987A.

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VANDELS: Exploring the Physics of High-redshift Galaxy Evolution

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VANDELS is a new ESO spectroscopic Public Survey targeting the high-redshift Universe. Exploiting the red sensitivity of the refurbished VIMOS spectrograph, the survey is obtaining ultra-deep optical spectroscopy of around 2100 galaxies in the redshift interval $1.0 < z < 7.0$, with 85 % of its targets selected to be at $z \geq 3$. The fundamental aim of the survey is to provide the high signal-to-noise spectra necessary to measure key physical properties such as stellar population ages, metallicities and outflow velocities from detailed absorption-line studies. By targeting two extragalactic survey fields with superb multi-wavelength imaging data, VANDELS will produce a unique legacy dataset for exploring the physics underpinning high-redshift galaxy evolution.

Background

Understanding the formation and evolution of galaxies, from the collapse of the first gas clouds at early times to the assembly of the detailed structure we observe in the local Universe, remains the key goal of extragalactic astronomy. Despite the immense challenge, the last 15 years have been a period of unprecedented progress in our understanding of the basic demographics of high-redshift galaxies. Indeed, thanks largely to the profusion of deep, multi-wavelength survey fields, we now have a good working knowledge of how the galaxy luminosity function, stellar mass function and global star formation rate density evolve with redshift (see Madau & Dickinson, 2014 for a recent review).

As a consequence, we can now be confident that the star formation rate density we observe locally is approximately the same as it was less than a billion years after the Big Bang (i.e. $z \sim 7$), and that in the intervening period the Universe was forming stars about ten times more rapidly. However, despite this it is still perfectly plausible to argue that the peak in cosmic star formation history occurred anywhere in the redshift interval $1.5 < z < 3.5$, an uncertainty of two and a half billion years. Moreover, the results of the latest generation of semi-analytic and hydro-dynamical galaxy simulations (for example Somerville & Davé, 2015) demonstrate that, from a theoretical perspective, even reproducing the evolution of the cosmic star formation density can be problematic.

Over the last decade it has become clear that the majority of cosmic star formation is produced by galaxies lying on the so-called main sequence of star formation (Noeske et al., 2007). The main sequence is a roughly linear relationship between star formation rate (SFR) and stellar mass, the normalisation of which increases with lookback time. Galaxies lying well above the main sequence can be considered to be starbursts, while those falling well below the main sequence are passive, or quenched.

The evolution in the normalisation of the main sequence over the last 10 Gyr is now relatively well established, with the average SFR at a given stellar mass increasing by a factor of about 30 between the local Universe and redshift $z = 2$ (for example, Daddi et al., 2009). However, at higher redshifts the evolution of the main sequence is still uncertain, despite a clear theoretical prediction that it should mirror the increase in halo gas accretion rates (for example, Dekel et al., 2009). Depending on their assumptions regarding star formation histories, metallicity, dust and nebular emission, different studies find that at a given stellar mass the increase in average SFR between $z = 2$ and $z = 6$ is anything from a factor of about two (for example, González et al., 2014), to a factor of about 25 (for example, de Barros et al., 2014).

Moreover, although the decline in the global star formation rate density over the last 10 Gyr has been well characterised, the primary physical drivers responsible for this quenching remain uncertain. With varying degrees of hard evidence and speculation, active galactic nuclei (AGN) feedback, stellar winds, merging and environmental-/mass-driven quenching have all been widely discussed in the literature (see Fabian, 2012 and Conselice, 2014 for reviews). It seems clear that quenching must be connected to the interplay between gas outflow, the inflow of "pristine" gas, the build-up of the mass-metallicity relation and morphological transformation. However, to date, the relative importance of, and interconnections between, the different underlying physical mechanisms remain unclear.

Within this context, a series of spectroscopic campaigns with the Very Large Telescope (VLT) and the VIsible Multi-Object Spectrograph (VIMOS), such as the VIMOS Very Deep Survey (VVDS; Le Fèvre et al., 2005), the COSMOS spectroscopic survey (zCOSMOS; Lilly et al., 2007) and the VIMOS Ultra Deep Survey (VUDS; Le Fèvre et al., 2015), have played a key role in improving our understanding of galaxy evolution, primarily through providing large numbers of spectroscopic redshifts over wide fields. The VANDELS survey is designed to complement and extend the work of these previous campaigns by focusing on ultra-long exposures of a relatively small number of galaxies, pre-selected to lie at high redshift using the best available photometric redshift information.

The survey

The VANDELS (Proposal ID 194.A-2003) survey is repeatedly targeting a total of eight overlapping VIMOS pointings (see Figure 1), four in the United Kingdom InfraRed Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS) Ultra Deep Survey (UDS) and four in the Chandra Deep Field South (CDFS). VANDELS observations are exclusively performed using the medium resolution (MR) grism + GG475 order-sorting filter, which provides medium resolution ($R \sim 700$) spectra covering the wavelength range 4800–10 000 Å at a dispersion of 2.5 Å pixel^{-1}.

Each of the eight pointings is observed four times, each pass receiving 20 hours of on-source integration. Using a nested slit allocation strategy, targets are allocated either 20, 40 or 80 hours of integration, depending on their brightness. In total, VANDELS has been allocated 640 hours of on-source observing time, all of which is being obtained in Visitor Mode on the VLT between August 2015 and January 2018.

In order to justify such a large investment of observing time, VANDELS is deliberately focused on two of the best legacy fields for studying the high-redshift Universe. Crucially, both the UDS and CDFS are covered by deep optical–near-infrared Hubble Space Telescope (HST) imaging provided by the CANDELS survey (Grogin et al., 2011). In addition, both UDS and CDFS are covered by ultra-deep imaging with the Spitzer Space Telescope, HST near-infrared grism spectroscopy from the public 3D-HST survey (Brammer et al., 2012) and the deepest available *Y*+*K*-band imaging from the HAWK-I Ultra Deep Survey (HUGS; Fontana et al., 2014).

The fundamental science goal of VANDELS is to move beyond simple redshift acquisition and obtain a spectroscopic dataset deep enough to study the astrophysics of high-redshift galaxy evolution. The spectroscopic targets are all pre-selected using high-quality photometric redshifts, the vast majority being drawn from one of three main categories: bright star-forming galaxies, higher redshift star forming galaxies and passive galaxies.

Firstly, VANDELS is targeting a sample of more than 400 bright ($H_{AB} \leq 24$, $I_{AB} \leq$ 25 mag.) star-forming galaxies in the redshift range $2.4 < z < 5.5$. The spectra of these galaxies will cover the required rest-frame ultraviolet (UV) wavelength range with a signal-to-noise ratio (SNR) high enough to allow the stellar metallicity to be measured. Secondly, the VANDELS survey extends to higher redshifts and fainter magnitudes by targeting a large sample (around 1300) of star-forming galaxies at $3 < z < 7$ in the magnitude range ($25 < i_{AB} < 27$). Thirdly, to study the descendants of high-redshift star-forming galaxies, VANDELS also uses rest-frame *UVJ* selection (Williams et al., 2009) to target a complementary sample of around 300 massive ($H_{AB} \leq 22.5$), passive galaxies at $1.0 < z < 2.5$. Finally, thanks to the large number of targets that can be

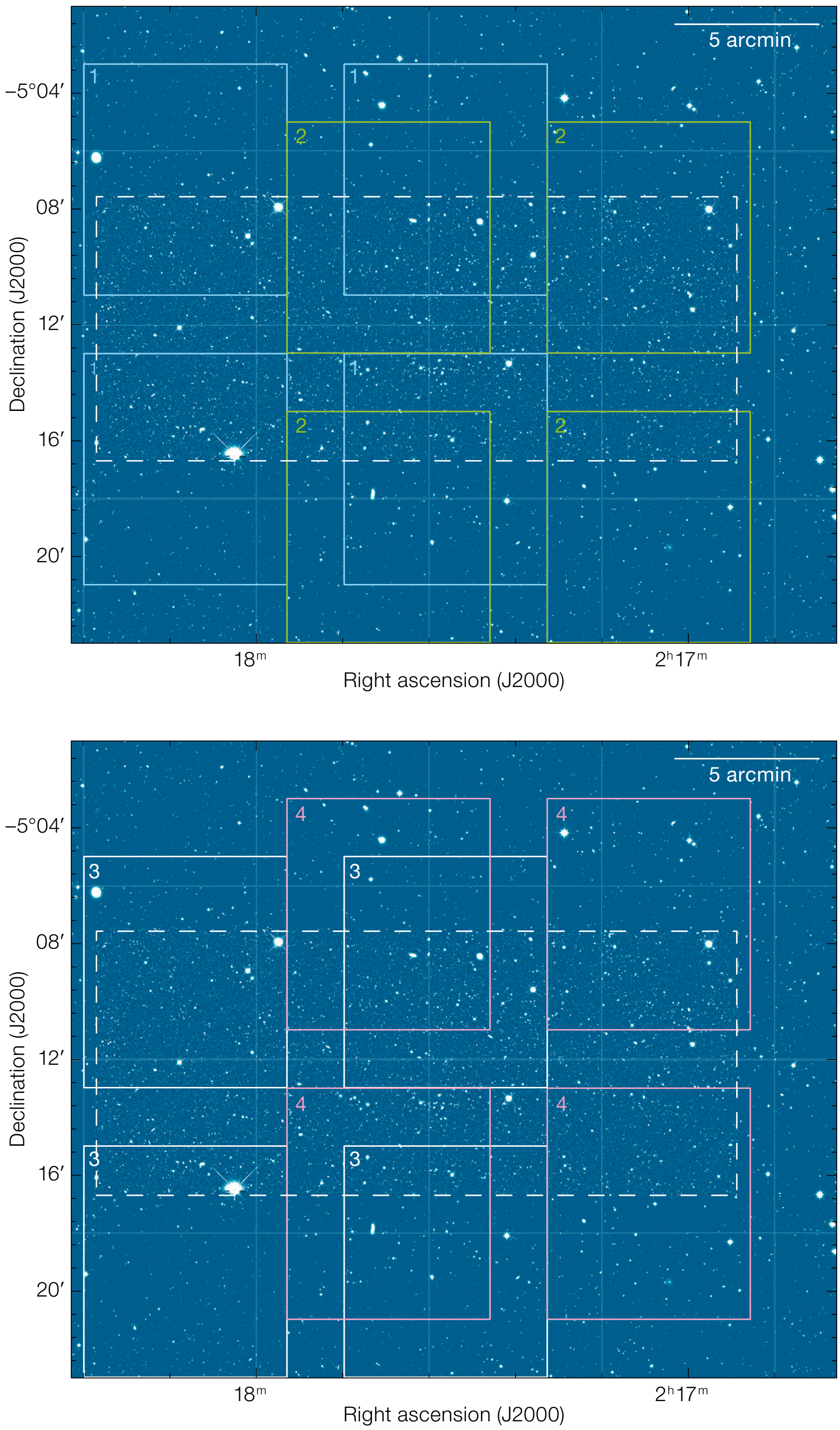

Figure 1. Illustration of how the four VANDELS VIMOS pointings are organised within the UDS survey field. The rectangle indicated by the dashed white line shows the region covered by deep *H*-band HST imaging from the CANDELS survey. The four VIMOS pointings (labelled 1–4), each with four quadrants, are located to ensure that 100 % of the HST imaging area is covered. Outside the central region, the background image shows the deep *H*-band imaging from the UKIDSS UDS survey. To maximise the slit allocation efficiency, targets can be allocated to slits on quadrants in different overlapping pointings. The four pointings within the CDFS survey fields are organised in a similar fashion.

allocated on each VIMOS mask, VANDELS is also targeting small samples of rarer bright systems such as AGN and galaxies detected by the Herschel satellite.

The VANDELS observing strategy is designed to provide consistently high SNR continuum detections for the bright star-forming and passive galaxy sub-samples (see Figure 2 for example spectra). For those objects with $i_{AB} \leq 24.5$, the final 1D spectra will typically provide SNR of 15–20 per resolution element, based on total exposure times of 20, 40 or 80 hours. For the faintest objects in these sub-samples ($i_{AB} \sim 25$), the final spectra typically have a SNR ~ 10 per resolution element, based on 80 hours of integration. For the faintest ($25 < i_{AB} < 27$) targets at $z \geq 3$, the VANDELS observing strategy is designed to provide a consistent Ly-α emission-line detection limit (5σ) of ~ 2×10^{-18} erg s^{-1} cm^{-2} and a continuum SNR of about 3 per resolution element. The data reduction and survey management of VANDELS are performed within the *Easylife* system (Garilli et al., 2012). *Easylife* is an updated version of the original VIMOS Interactive Pipeline and Graphical Interface (VIPGI) system and was originally developed to process the data from the VIMOS Public Extragalactic Redshift Survey (VIPERS; Guzzo et al., 2014).

Science goals

As outlined briefly above, current studies of high-redshift galaxies are limited by interrelated and insidious uncertainties in the measurements of key physical parameters such as stellar mass, metallicity, star formation rate and dust attenuation. The VANDELS survey is specifically designed to provide the high-SNR spectra necessary to derive accurate physical parameters via absorption line studies,

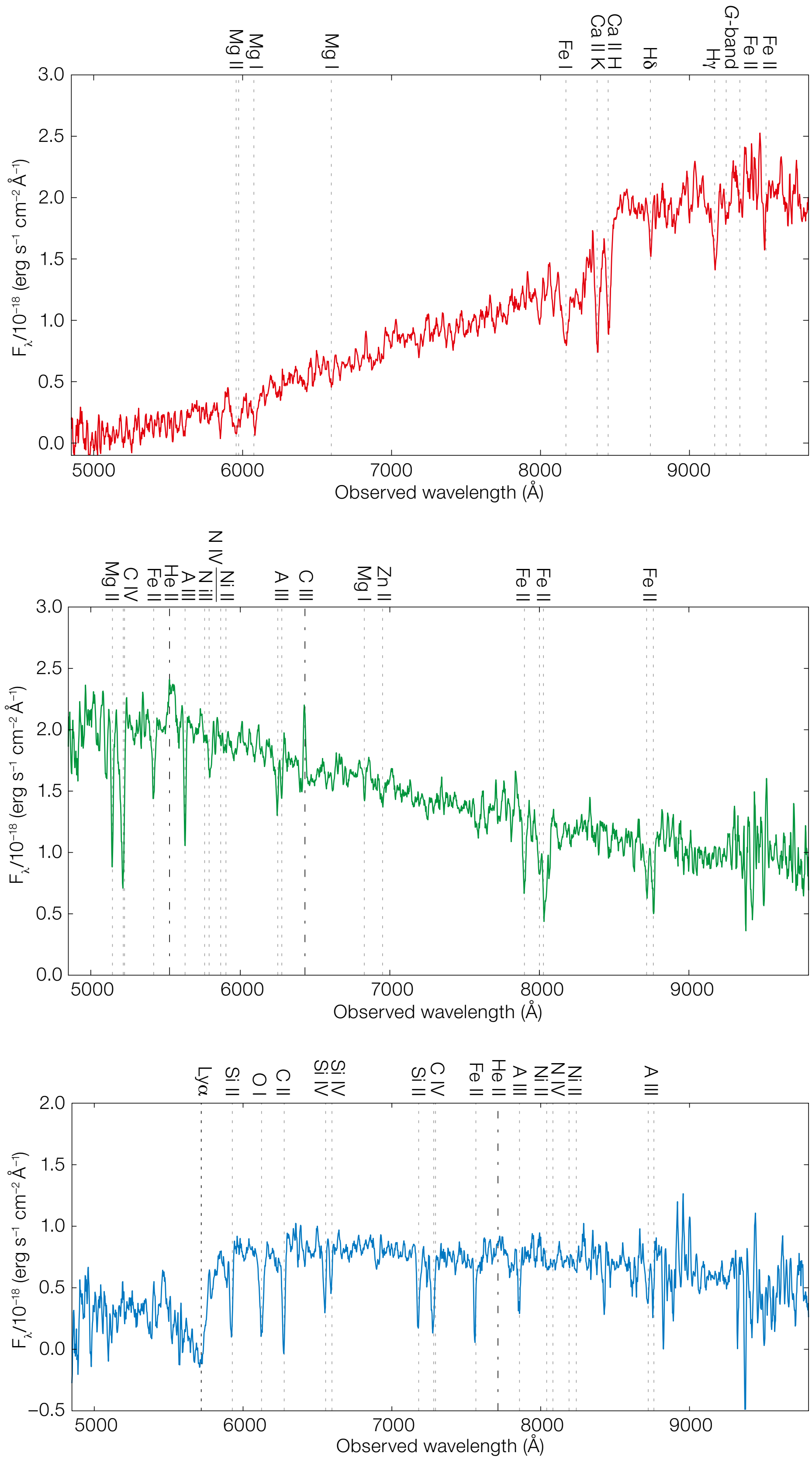

Figure 2. Example spectra from the VANDELS survey. The top panel shows a redshift $z = 1.1303$ passive/quiescent galaxy. The middle panel shows a bright star-forming galaxy at $z = 2.372$ and the bottom panel shows a bright star-forming galaxy at $z = 3.703$. Common absorption (dotted lines) and emission (dot-dashed lines) features are highlighted. For the type of objects shown, the VANDELS observations are designed to provide spectra with sufficiently high SNRs to allow key physical properties (for example, metallicity and outflow velocities) to be measured on an individual, object-by-object, basis.

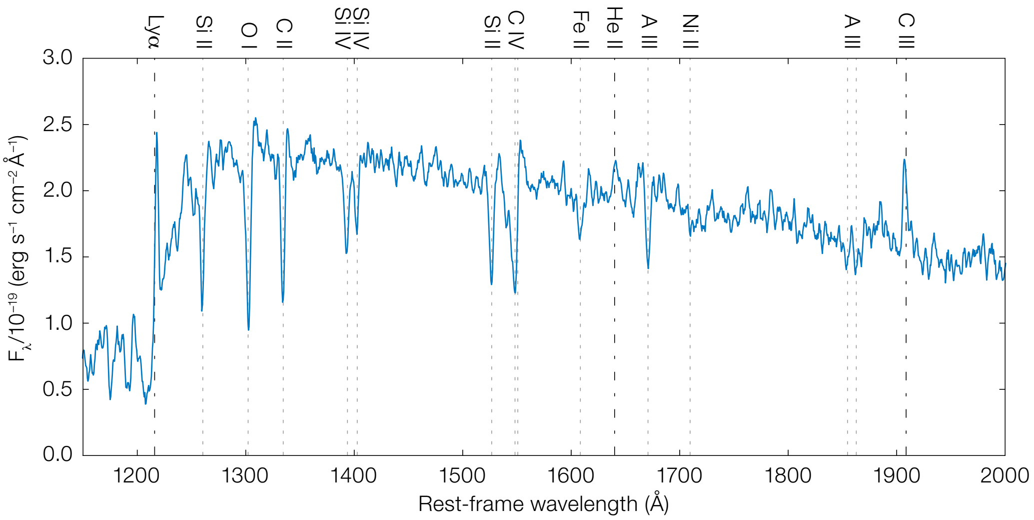

Figure 3. An illustration of the potential within the VANDELS dataset for producing high-SNR stacked spectra. This example shows the stacked spectrum of 100 fainter star-forming galaxies in the redshift interval $3.0 < z < 4.0$. Common absorption (dotted lines) and emission (dot-dashed lines) features are highlighted. The stacked spectra from VANDELS will allow key physical properties to be investigated over a wide dynamic range in redshift, stellar mass and star formation rate.

and will therefore have an impact on many areas of high-redshift galaxy evolution science. However, the original VANDELS survey proposal was motivated by a small number of key science goals, three of which we briefly discuss below.

1. Stellar metallicity and dust attenuation
Tracing the evolution of metallicity is a powerful method of constraining high-redshift galaxy evolution via its direct link to past star formation and sensitivity to interaction (inflow/outflow) with the intergalactic medium. Moreover, accurate knowledge of metallicity is essential for deriving accurate star formation rates and breaking the degeneracy between age and dust extinction (for example, Rogers et al., 2014).

Recent studies using stacked spectra of relatively small samples (for example, Steidel et al., 2016) have shown that it is possible to derive accurate stellar metallicities from the rest-frame UV spectra of galaxies at $z \geq 2$, provided the spectra have a high enough SNR. The VANDELS data will allow metallicities to be measured for hundreds of galaxies at $2.4 < z < 5.5$, both individually and via stacking (see Figures 2 and 3) and therefore offers the prospect of transforming our understanding of metallicity at high redshift.

It is worth noting that the ability to independently constrain the stellar metallicity and dust attenuation (from the ratio of observed to intrinsic UV spectral slopes) will also lead to significantly improved estimates of stellar masses and SFRs. Importantly, this means that the VANDELS dataset will allow the stellar mass – stellar metallicity relation to be studied out to $z \sim 5$ for the first time. Moreover, the improved stellar mass and SFR estimates for about 1800 spectroscopically confirmed star-forming galaxies at $2.4 < z < 7.0$ will also allow accurate calibration of photometric determinations of the evolving stellar mass and SFR functions.

2. Outflows
Along with stellar metallicity measurements, a key science goal for VANDELS is the study of outflowing interstellar gas. It is now becoming increasingly clear that high-velocity outflows may be ubiquitous amongst star forming galaxies at $z > 1$, with mass outflow rates comparable to the rates of star formation (for example, Bradshaw et al., 2013). Such outflows may be playing a major role in the termination of star formation at high redshift and the build-up of the mass–metallicity relation.

Crucially, the high-SNR, medium-resolution, VANDELS spectra will allow accurate measurements of outflowing interstellar medium velocities from high- and low-ionisation UV interstellar absorption features (for example, Shapley et al., 2003). The fundamental goal is to measure the outflow rate as a function of stellar mass, SFR, and galaxy morphology, in order to understand the impact of galactic outflows on star formation at $z \geq 2$. Measuring the balance of inflow, outflow and star formation will enable models of the evolving gas reservoir to be tested and address the origins of the Fundamental Metallicity Relation (Mannucci et al., 2010). Finally, comparing the outflow velocities of star-forming galaxies with and without hidden AGN (as identified from X-ray emission) will allow the role of AGN feedback in quenching star formation and the build-up of the red sequence to be investigated.

3. Massive galaxy assembly and quenching
A key sub-component of VANDELS is obtaining deep spectroscopy of ~300 massive, passive galaxies at $1.0 < z < 2.5$. This population holds the key to understanding the quenching mechanisms responsible for producing the strong colour bi-modality observed at $z < 1$, together with the significant evolution in the number density, morphology and size of passive galaxies observed between $z = 2$ and the present day. For the majority of the passive sub-sample, the VANDELS spectra will provide a combination of crucial rest-frame UV absorption-line information and Balmer break measurements. Combined with the unrivalled photometric data available in the UDS and CDFS fields, it will be possible to break age/dust/metallicity degeneracies and deliver accurate stellar mass, dynamical mass, star formation rate, metallicity and age measurements via full

spectrophotometric spectral energy distribution (SED) fitting.

Legacy science

Finally, given that VANDELS is fundamentally a public spectroscopic survey, it is worth briefly considering the question of legacy science. The immense legacy value of the VANDELS survey is compelling: simply by providing spectra of relatively faint targets with unprecedentedly high signal-to-noise, VANDELS is guaranteed to open up new parameter space for investigating the physical properties of high-redshift galaxies. For example, VANDELS will fundamentally improve our knowledge of the statistics of Ly-α emission in star-forming galaxies approaching the reionisation epoch (see Pentericci et al., 2014) and expedite the identification of the progenitors of compact galaxies amongst star-forming galaxies at $z \geq 2.5$. Moreover, additional science will be facilitated by the samples of rarer bright systems, such as the Herschel detected galaxies and AGN, targeted by VANDELS. For these systems, the deep VANDELS spectroscopy will make it possible to assess their physical conditions (for example, metallicities, ionising fluxes and outflow signatures) and compare them with those of less active systems at the same redshifts.

In terms of future follow-up observations, there is an excellent synergy between VANDELS and the expected launch date of the James Webb Space Telescope (JWST) in late 2018. The opportunity to combine ultra-deep optical spectroscopy with the unparalleled near-infrared spectroscopic capabilities of the JWST near-infrared spectrograph NIRSpec will make VANDELS sources an obvious choice for follow-up spectroscopy with JWST. As a specific example, high-SNR spectra of the Balmer break region of typical $z \sim 5$ galaxies targeted by VANDELS could be obtained with NIRSpec in less than one hour.

Finally, it is also worth noting that the southern position of both the UDS and CDFS make them ideal survey fields for sub-millimetre and millimetre wavelength follow-up observations with the Atacama Large Millimeter/submillimeter Array (ALMA). One of the key scientific questions that VANDELS will help to address is the evolution of star formation and metallicity in galaxies at $z \geq 2$. However, in order to derive a complete picture it will be necessary to obtain dust mass and star formation rate measurements at long wavelengths, which can now be provided by short, targeted, continuum observations with ALMA.

Timeline

The VANDELS survey has just finished its second of three observing seasons and, weather depending, is scheduled to be completed in January 2018. All of the raw data are immediately available for download via the ESO Science Archive Facility (SAF). In addition, the VANDELS team are committed to a regular schedule of data releases (starting with data release 1 in June 2017), through which fully reduced 1D and 2D spectra, plus redshifts and basic target parameters, will be provided to the astronomy community via the SAF. More information about the VANDELS survey, including a full list of Co-Is, can be found at the team website[1].

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[1] VANDELS team website: http://vandels.inaf.it

Part of the Chandra Deep Field South (10.1 × 10.5 arcminutes) imaged by the Wide Field Imager on the MPG/ESO 2.2-metre telescope shown in a *B*-, *V*- and *R*-band composite. See Release eso0302 for further details.

ESO/G. Hüdepohl (atacamaphoto.com)

Aerial image of the Paranal Observatory shortly before sunset. The VISTA peak is to the left (north-east) and the Residencia and support buildings to the south-east. See ESO Picture of the Week potw1650a for details.

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Report on the

2017 ESO Calibration Workshop: The Second-Generation VLT Instruments and Friends

held at ESO Vitacura, Santiago, Chile, 16–19 January 2017

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The participants at the 2017 ESO Calibration Workshop shared their experiences and the challenges encountered in calibrating VLT second-generation instruments and the upgraded first-generation instruments, and discussed improvements in the characterisation of the atmosphere and data reduction. A small group of ESO participants held a follow-up retreat and identified possible game changers in the future operations of the La Silla Paranal Observatory: feedback on the proposals is encouraged.

Figure 1. The attendees at the 2017 Calibration Workshop photographed in the garden of ESO Vitacura.

Introduction

Calibration is a critical component in the conversion of raw data to material ready for scientific analysis. Consequently, a complete, consistent calibration plan for each dataset fulfilling quality control criteria was recognised as a cornerstone of the operation of the Very Large Telescope (VLT). In 2007, ESO organised its first Calibration Workshop (Kaufer & Kerber, 2007) in order to: (a) foster the sharing of information, experience and techniques between observers, instrument developers and the instrument operation teams; (b) review the actual precision and limitations of the applied instrument calibration plans; and (c) collect the current and future requirements of the ESO users. The first Calibration Workshop focused on calibration issues affecting the first generation of VLT instruments.

Ten years later, ESO instrumentation has changed considerably following the arrival of second-generation instruments — the *K*-band Multi-Object Spectrograph (KMOS), the Multi Unit Spectroscopic Explorer (MUSE), the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) and the X-shooter spectrograph — and the completion of major upgrades of first-generation ones, such as the High Accuracy Radial velocity Planet Searcher (HARPS) and the VLT Imager and Spectrometer for mid-InfraRed (VISIR). In the near future, it will evolve further with the completion of the upgrade of the CRyogenic InfraRed Echelle Spectrometer (CRIRES) to CRIRES+, the arrival of the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) and the adaptive-optics-assisted instrument modes of MUSE and the High Acuity Wide-field *K*-band Imager (HAWK-I). In addition, other instruments are in plan: SOn of X-Shooter (SOXS) and the Near InfraRed Planet Searcher (NIRPS) at La Silla; the Enhanced Resolution Imaging Spectrograph (ERIS) and the Multi Object Optical and Near-infrared Spectrograph (MOONS) at the VLT; and the 4-metre Multi-Object Spectroscopic Telescope (4MOST) at the Visible and Infrared Survey Telescope for Astronomy (VISTA). For many of these instruments, the increase in complexity requires challenging calibration to achieve optimum performance.

The 2017 ESO Calibration Workshop brought together astronomers and instrument scientists from various fields of expertise to share their experience, engage in open discussions, challenge current limitations and try to develop creative concepts for better calibration in the future. The workshop covered:
- all aspects of calibration that are relevant to the user community or to science operations at ESO's Paranal (VLT) and La Silla sites;
- the progress made in characterising the properties of the atmosphere that allow science operations to make the best use of current conditions;
- progress made in data reduction and pipeline tools.

The ESO office in Vitacura was chosen as the venue for the workshop to foster collaboration between the major ground-based observatories in Chile. The sunny weather also allowed the participants to enjoy lunches and the conference dinner in the pleasant gardens; see Figure 1.

The workshop

The participants — from ESO Headquarters in Garching and from the Chile sites, from various institutes in Europe, from Gemini Observatory, Las Campanas Observatory, the Large Synoptic Survey Telescope (LSST) project, US National Institute of Standards and Technology (NIST), the Pontificia Universidad Catolica de Chile (PUC), the Center for Astronomy in Harvard, USA, and the Space Telescope Science Institute (STScI) in Baltimore, USA — listened to presentations grouped in sessions organised around a central theme. Most of the sessions included: (i) a talk describing an ESO instrument, its calibration plan and issues affecting the quality of the data; (ii) an invited talk, or several, on the specific theme of the session; and (iii) contributed talks on various calibration or data reduction aspects. Ample time was left after each presentation, and at the end of each session, for lively discussion.

The themes of the various sessions were focused: on calibration of adaptive-optics-fed instruments (SPHERE); infrared spectroscopy and metrology; high-accuracy wavelength calibration (such as for HARPS, ESPRESSO, and the Giant Magellan Telescope [GMT] Consortium Large Earth Finder [G-CLEF]); reference data (molecular line parameters and atomic lines used for wavelength calibration); lessons learned from past instruments regarding polarimetry; calibrations for integral field units and sky background reduction strategies in multi-fibre spectrographs; photometry; astrometry; the Earth's atmosphere; wide-field surveys, as obtained by VISTA's infrared camera VIRCAM or the future LSST; and data reduction.

The concluding remarks by Susanne Ramsay (ESO) crystallised various themes which often appeared in the various presentations. For example, is calibration a tool to fix hardware issues: can that step be avoided by improving instrument design? Can we rely on physical instrument models instead? However, since everything changes, one must be always attentive and constantly assess the quality of calibrations and their validity period (*semper vigilo*): calibration plans are living things. But this task should not keep us from being more ambitious, for example in attempting to reduce the time spent on sky-subtraction in the near infrared. Interaction with users is also a key input: data that cannot be reduced do not return any science! Finally, ESO should prepare now and respond to the challenges to be presented by LSST and the European Space Agency (ESA) Gaia satellite, and for the new instrumentation on the 40-metre-class Extremely Large Telescope.

An innovative feature of the meeting was that technical time on the VLT (and on the ESO 3.6-metre) was pre-allocated in preparation for the calibration workshop. This observing time will be used to execute novel and innovative self-contained calibration methods and concepts. A specific session was organised to present their content and merit to all participants at the workshop. These calibration proposals will then be executed during pre-allocated time in due course.

All the presentations, recordings and question-and-answer sessions will soon be available on Zenodo[1] or through the workshop webpage[2].

The retreat

After the workshop, a small group of ESO participants met at Paranal for a retreat. They identified the following potentially game-changing topics or actions for the operation of the La Silla Paranal Observatory, which were then ordered on a 2D graph of "scale of impact" *vs* "likelihood of execution":

1. The integration of the high-accuracy astrometric and photometric data, obtained by Gaia, LSST and surveys like the VISTA Hemisphere Survey (VHS), into ESO operations was recognised by all as the most likely to happen with the largest impact. Aspects that will be impacted range from the calibration of the telescope adaptors, the internal astrometric calibration of instruments like KMOS, to data reduction, on the basis that most fields will have a sufficiently high density of stars for accurate astrometric and photometric calibrations.
2. Another potentially high-impact topic is how to better characterise the state of the atmosphere and, based on that, how to forecast relevant atmospheric parameters, along with which data should be used for optimal processing of adaptive optics data reduction and analysis? An accurate atmospheric profile is also required for optimal correction of telluric absorption lines by tools such as Molecfit (Smette et al., 2015; Kausch et al., 2015). What will be the impact of high-accuracy forecasts (in particular, of the turbulence including the seeing) on observations within a time frame of hours to days?
3. Physical modelling of the instrument behaviour was best illustrated by the talk by Robert Lupton on LSST. Ideas that were identified included an exposure time calculator (ETC) callable by a user script, which can also be used to systematically compare observations with expectations and to analyse hardware problems. Furthermore, how could an ETC be used for calibration — potentially reducing the number and frequency of on-sky calibrations — and how best to follow up on this approach when comparing the model with reality?
4. Presentations by Miwa Goto on infrared spectroscopy and Florian Kerber on the Low Humidity ATmospheric PROfiling radiometer (LHATPRO: Kerber et al., 2012) indicated that the VLT could "fly" when certain conditions occur: the amount of precipitable water vapour above Paranal can occasionally be the same as on a site at 5000 metres (Kerber et al., 2014)! On the other hand, the number of programmes requesting the best seeing conditions is small. If the opportunities are rare, how could the Observatory best make use of them? ESO should promote programmes whose science can only be carried out under excellent conditions. The Call for Proposals for Period 100 will already mention this concept, which could be reinforced in future calls once the implications are better evaluated.
5. Should the calibration strategy be better matched to the requested science? At one extreme, we could imagine that users provide not only their science Observing Blocks, but also all their Calibration Blocks. The content of such Calibration Blocks would also be based on an ETC to ensure that the quality of the science data is not degraded, for example due to insufficient signal-to-noise ratio in the flat fields.
6. Instrument Operations Teams ensure that instruments provide the best science and calibration data. They should, however, be encouraged to contact expert users in the community to promote collaboration with ESO and disseminate the knowledge to the wider community, or to identify specific problems with an instrument.
7. Does the ELT have specific calibration requirements which can only be addressed by specific VLT observations? The next few years should be used to first identify these needs and

then define and conduct the relevant observations.
8. New calibration sources such as Laser Frequency Combs or stable Fabry-Pérot calibration units will soon become operational at ESO: what is their potential for other VLT instruments? Problems with high-purity Thorium-Argon hollow-cathode lamps following recent stricter environmental regulations could be dealt with by a bulk order in collaboration with other observatories.
9. ESO should take a more active role in defining the needs for laboratory data. Archival data may play a crucial role to improve molecular line parameters which are required for accurate, synthetic telluric line correction in tools such as Molecfit.

The participants in the retreat compiled and agreed on a list of action items to further explore these different topics and transform them into specific improvements for their integration into ESO operations. These action items and the corresponding deadlines will be pursued in order to ensure progress towards a timely implementation.

Conclusions

According to the feedback received, the 2017 ESO Calibration Workshop succeeded in its aim of encouraging discussion of calibration issues, not only for ESO instruments but also at other ground-based observatories. Seeds of potential game changers in improving ESO future operations were identified and need to be brought to fruition. We encourage everyone interested in the subject to further explore these topics with us through the email account calibration2017@eso.org.

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[1] Zenodo: http://www.zenodo.org
[2] Conference web page: http://www.eso.org/sci/meetings/2017/calibration2017.html

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Highlights from the CERN/ESO/NordForsk

Gender in Physics Day

held at CERN, Geneva, Switzerland, 27 January 2017

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In their role as observers on the EU Gender Equality Network in the European Research Area (GENERA) project, funded under the Horizon 2020 framework, CERN, ESO and NordForsk joined forces and organised a Gender in Physics Day at the CERN Globe of Science and Innovation. The one-day conference aimed to examine innovative activities promoting gender equality, and to discuss gender-oriented policies and best practice in the European Research Area (with special emphasis on intergovernmental organisations), as well as the importance of building solid networks. The event was very well attended and was declared a success. The main highlights of the meeting are reported.

GENERA and its objectives

The Gender Equality Network in the European Research Area (GENERA) is a Horizon 2020 project that focuses on evaluating, monitoring and improving existing or new gender equality plans of research organisations in the field of physics. The GENERA Consortium includes 13 beneficiary partners, either Research Performing Organisations (RPOs) or Research Funding Organisations (RFOs) scattered across Europe, and a number of associate partners and observers. Among the latter, CERN (the European Organization for Nuclear Research), NordForsk (an organisation that facilitates and provides funding for Nordic research cooperation and research infrastructure) and ESO, follow the GENERA activities very closely. The first meeting of the project was held at ESO's Headquarters in June 2015. The final goal of GENERA is very ambitious, i.e., to propose and create organisational structures allowing physics research in Europe to benefit from a more gender-balanced research community.

Within the GENERA network, one special initiative that looks in more detail at national gender equality plans and at the existence of innovative activities that help with the gender balance, is the organisation of national Gender in Physics Day (GiPD) events. Each of the 13 beneficiary partners is expected to organise one such event in their own country. Each event follows common organisational guidelines that consist of collecting a general overview on the national situation (both in terms of gender statistics and initiatives) and offering topical workshops in the areas most relevant to that country.

NordForsk

Figure 1. The discussion forum on gender statistics and equality plans among the EIROforum organisations. From left to right: Ms Ersilia Vaudo (ESA, Head of Policy Office); Ms Heidi Schmidt (ESO, Head of Human Resources); Mr. James Purvis (CERN, Head of Talent Acquisition); Mr. Thierry Baudoin (ESRF, Head of Human Resources).

The CERN/ESO/NordForsk GiPD

In this spirit, CERN, NordForsk and ESO decided to organise a Gender in Physics Day, bringing in the perspective of intergovernmental organisations and the challenges that such international research infrastructures and funding agencies face. All eight EIROforum organisations were invited to join the event. The focus of the day was on the recruitment, retention and career development of female professionals in the field of science, engineering and technology (SET).

The event was meant to be an opportunity to discuss with the academic partners within GENERA the issue of a sustainable scientific or engineering career after Masters, PhD or Postdoctoral employment. All the international research organisations were asked ahead of the meeting to share their gender disaggregated data, as well as measures implemented in their infrastructure, with a critical view on their effectiveness. NordForsk has been funding efforts on the issue of gender balance for years and the focus on the field of physics was meant to serve as a case study for other fields. NordForsk therefore brought insight into the situation in the Nordic countries: from how they support collaborations with the large infrastructures in Europe to what is their gender (im)balance in physics.

This GiPD also offered an opportunity to reflect on how gender equality, and more generally diversity, can be embedded in international collaborations or consortia, to look at the situation of women in physics in developing countries, and to listen to the expectations of the younger generation.

The programme alternated panel discussions, talks, interactive sessions and workshops and aimed at targeting a varied audience, ranging from junior and senior researchers to management-level personnel, policy makers and diversity officers. The event was attended by about 100 people. All eight EIROforum organisations were represented at the venue, as well as four Nordic countries (Denmark, Finland, Norway and Sweden) and members of the largest projects and scientific collaborations in the current physics world (for example, the ATLAS experiment and the Compact Muon Solenoid [CMS] experiment, both at CERN).

Highlights from the plenary sessions

The day opened with welcome speeches by the CERN and ESO Directors General (Fabiola Giannotti and Tim de Zeeuw, respectively) and by the NordForsk Senior Adviser (Lotta Strandberg), wishing all participants a productive meeting and noting their important exchanges on best practice and future collaborations.

After an introduction and progress report on GENERA by its Programme Coordinator, the morning was divided into three main sessions: Gender Equality Plans and Numbers in international RPOs; Efforts in Gender Equality and Results in the Nordic Countries; and Other Perspectives.

The first session focused on a direct comparison of gender statistics among some of the EIROforum institutes. Numbers were collected and assembled beforehand so that the session could be structured as a discussion forum, with representatives of the European Space Agency (ESA), the European Synchrotron Radiation Facility (ESRF), ESO and CERN on stage. Not surprisingly, numbers turned out to be rather similar, confirming that all four organisations are facing similar challenges, especially as regards hiring and retaining female scientists and promoting them to the top levels. In the field of engineering, where from the start the pool of female candidates is already significantly smaller, numbers appear to be even more challenging.

The second session was dedicated to the Nordic countries. NordForsk was the main host of this part of the programme that included detailed overviews of the gender (im)balance in physics in Denmark, Norway and Sweden. In terms of gender equality, the Nordic countries have rather paved the way over the past several years, with dedicated legislation, special hiring/funding programmes and the setting of quotas (for example, on executive boards). While these measures have certainly had a positive impact in some areas and for some specific positions, all three presentations showed that, even if gender equality seems to have been achieved at college/Masters student levels, there remains a significant and increasing gap as the female researchers progress into their academic careers, with a persistent lack of senior female professors, similar to other countries (the so-called "Nordic Paradox").

The third session was a collection of different perspectives: from how to implement gender equality in large scientific collaborations and projects (for example, large high energy physics teams) to the situation in astronomy (noting the efforts the International Astronomical Union is making in this respect) and in the field of biology (with a detailed report from the EIROforum EMBL institute); to a look into the STEM fields (Science, Technology, Engineering and Mathematics) in developing countries. The last of those provided an insight into non-western cultures, where the majority of STEM students are actually female. The speaker presented the results of her investigations in Palestine and South Africa, underlining the cultural and socio-economic differences between those countries. The equal number of male and female STEM students at Bachelor and PhD level was explained as possibly due to the very different approach to advanced education. While in the western world, the young generation chooses College and Master degrees with an eye already on what they would like to do workwise afterwards, in, for example, Arab countries, college and Masters studies are still considered part of the basic education, and hence they choose what they really like to do, rather than what is expedient for a career. Unfortunately, they know from the start that the majority will not continue professionally, as there is a strong social pressure to get married and start a family.

Highlights from the workshops

After a networking lunch, the afternoon opened with an engaging and provocative talk on diversity, touching upon stereotypes, unconscious bias and work culture, followed by some reflections on gender imbalance in physics in Finland and different proactive measures that could be explored (from mentoring and leadership programmes to diversity and positive discrimination).

Participants then split into four parallel workshops: I. How to make a network; II. Promoting gender equality programmes (GEPs) in international consortia; III. Expectations from early career scientists on GEPs; and IV. Gender equality initiatives aimed at the general public (i.e., how to change the image of physics). A designated Chair moderated each discussion and collected feedback. All four workshops were well attended and discussion was lively and productive.

The day ended with brief reports from the workshop chairs, highlighting the main topics of discussion and conclusions that were reached. Workshop #1 looked into two types of networks, the EU GenPORT community project and the String Theory Universe, a Cost Action programme strictly focusing on the gender gap present in the field of string theory. The audience agreed that networks (especially social networks) represent important tools to raise awareness but they are not enough and they need a critical mass (which depends on goals, expertise and field) in order to be efficient.

Workshop #2 focused on the inclusion (or lack thereof) of GEPs in international consortia and organisations. Part of the discussion was centred on the LHCb collaboration, an international consortium (behind one of the CERN Large Hadron Collider [LHC] experiments) of more than 1200 members, involving 71 institutes in 16 countries. A constant monitoring of gender statistics with no evident improvement led the collaboration to set up an Early Career, Gender and Diversity Office inside LHCb, that now provides advice to the team management on equality and diversity issues. Raising awareness, improving working conditions and offering mentoring were among their final recommendations. EUROfusion, instead, presented the challenge of implementing gender equality guidelines and initiatives when the employment of staff is handled through beneficiaries, with every country having its own statutes, laws and (equality) best practice.

Workshop #3 focused on early-career scientists and touched upon their expectations in terms of gender and work-life balance. It was well attended by young physicists, who expressed concerns about the lack of transparency in hiring processes (even at postdoctoral levels), and the lack of role models or the existence of the wrong role models, especially in terms of balancing work and private life. Finally, Workshop#4 dealt with how the physics research field is presented to the general public. CERN presented two of its initiatives: one that targets an increase in diversity in CERN's public face via a variety of actions and public events; the other, gender inclusive teaching in the CERN High School teacher programme. One of the main outcomes here was about attracting and engaging young pupils in science, especially girls, thus breaking through stereotypes and expanding their knowledge.

Concluding remarks

Based on the feedback received, the day was declared a success, as it covered a variety of themes, some of which were not often covered in this type of event (for example, the challenges faced by inter-governmental organisations and the gender dimension of large scientific collaborations). More importantly, the event created the pre-requisites, especially among international organisations, to foster further exchanges on gender diversity and inclusivity actions.

Acknowledgements

The authors would like to thank all the participants for their support and active participation, especially the EIROforum representatives and the scientific societies in Denmark, Norway and Sweden for performing the data collection exercise to a very tight deadline. Special thanks go to the ESO and CERN directorships and senior management, for endorsing and attending the event. Finally, the organisers of this special Gender in Physics Day would like to thank the GENERA network and its Programme Coordinator for their support.

Links

[1] GENERA: http://genera-project.com
[2] NordForsk: https://www.nordforsk.org/
[3] EIROforum membership: European Organization for Nuclear Research (CERN), European Molecular Biology Laboratory (EMBL), European Space Agency (ESA), ESO, European Synchrotron Radiation Facility (ESRF), European Synchrotron Radiation Facility (XFEL), EUROfusion and Institut Laue-Langevin (ILL)
[4] GenPORT: http://www.genderportal.eu/

DOI: doi.org/10.18727/0722-6691/5009

Report on the

ESO Python Boot Camp — Pilot Version

held at ESO Vitacura, Santiago, Chile 13–14 October 2016

Bruno Dias[1]
Julien Milli[1]

[1] ESO

The Python programming language is becoming very popular within the astronomical community. Python is a high-level language with multiple applications including database management, handling FITS images and tables, statistical analysis, and more advanced topics. Python is a very powerful tool both for astronomical publications and for observatory operations. Since the best way to learn a new programming language is through practice, we therefore organised a two-day hands-on workshop to share expertise among ESO colleagues. We report here the outcome and feedback from this pilot event.

ESO/F. Rodriguez

Figure 1. (Above) Participants attended the morning classes with their own laptops running Python and all packages required by the Boot Camp.

Figure 2. (Below) Participants and trainers working together on the proposed projects, and interacting among different groups to share good ideas.

ESO/F. Rodriguez

The first step in launching Python at Vitacura was to hold a weekly informal coffee break centred on Python-related topics, called the ESO PyCoffee[1], which began in September 2015. Participants, from beginners to experts, shared their experience of using Python and demonstrated different applications of the language on a large diversity of astronomical problems. After a year with only presentations and discussions, we recognised a need for, and an interest in, more hands-on activities. We therefore started with the pilot version of the ESO Python Boot Camp, which took place on 13 and 14 October 2016. It was meant to be an internal event where the knowledge of more expert Python users could be shared. The main goal was to provide a basic training in Python for astronomers, telescope operators and engineers, to help them in their day-to-day tasks at the Observatory and in their own research. To achieve this goal, we placed particular emphasis on practical examples, so that trainees could leave the Boot Camp with a few scripts installed and running on their own computers.

The boot camp concept

We were not the first to organise a Python event focused on astronomy. To mention just a few cases, Berkeley[2] (the original), the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (NASA GSFC[3]) and the Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo (IAG-USP[4]), have all organised successful events similar to ours. The Python Boot Camp lasted two days, with classes during the mornings and projects in groups during the afternoons (see Figures 1 and 2). Two of the morning classes introduced the specific aspects of Python with respect to other languages, presented by the Paranal software engineer Claudio Reinero. The other classes were astronomy oriented and introduced tools useful in processing astronomical data. In some cases the trainers proposed exercises in real time using scripts or *Jupyter Notebooks*. These tools and the knowledge and good practice learned in the morning classes were later used to work on specific observatory projects during the afternoon sessions. Outlines of these projects are presented in the next section.

The participants were from many ESO departments: students, fellows, staff astronomers, telescope operators from Science Operations, data analysts from ALMA, and Paranal/La Silla engineers from various teams. Their background in

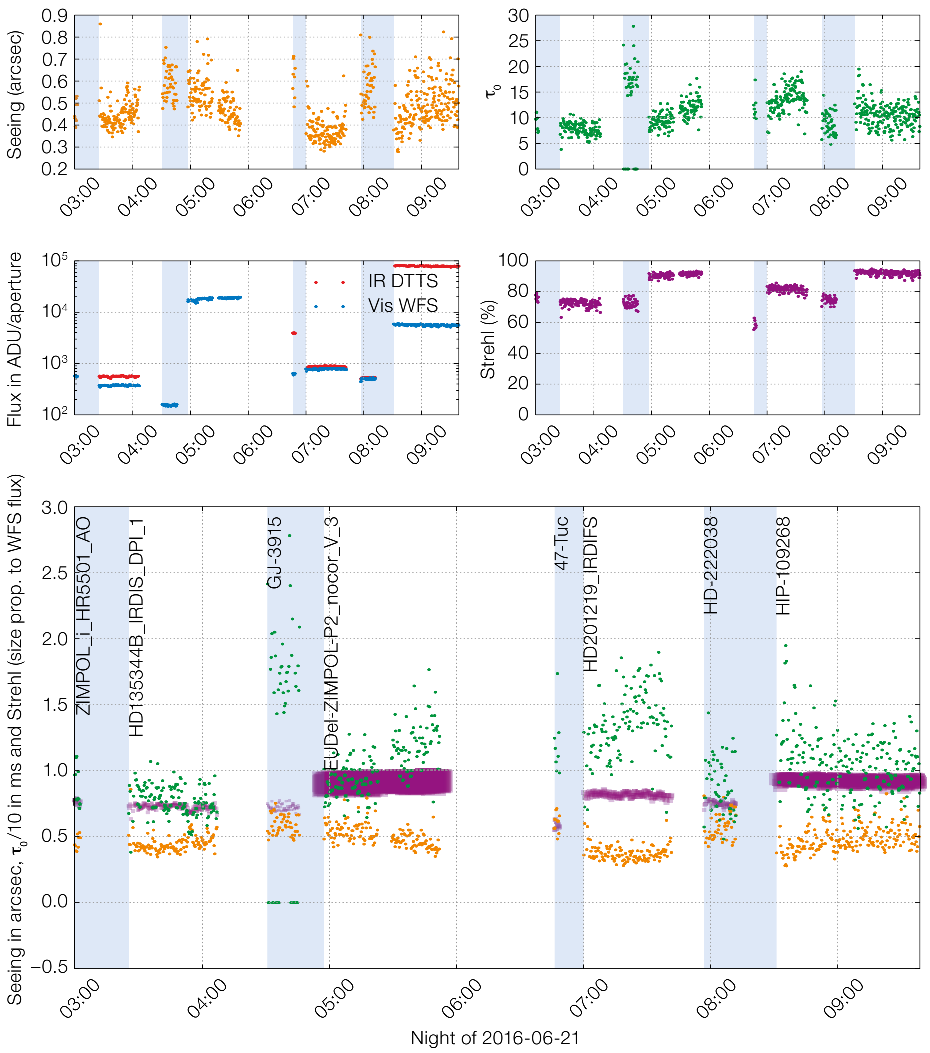


Figure 3. Evolution of weather conditions (seeing, coherence time [τ_0], flux and Strehl ratio), plotted in separate panels above, and combined in the large lower panel, as performed in Project 4.

Python ranged from complete beginners to experts. The diversity of backgrounds proved very fruitful during the interactions on the projects. The challenge, on the other hand, was to hold the attention of the more expert users without leaving the beginners behind.

Group projects

Project 1 — Focus curve of UVES

Leader: Nicolas Haddad (Paranal Instrumentation)

The participants had to analyse the differences in focus between the two chips of the Ultraviolet and Visual Echelle Spectrograph (UVES) detector and the focus evolution with time. In this project, skills such as manipulating a FITS (Flexible Image Transport System) image and header, extracting a spectrum from a 2D image, and measuring its full width at half maximum (FWHM) were developed.

Project 2 — Tracking the Strehl ratio of SINFONI during an Observing Block

Leader: Frédéric Vogt (Fellow)

This group had to analyse the evolution of the Strehl ratio during a given Observing Block (OB) for the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI). They extracted specific information from a complex text file containing the log, manipulated strings and time variables, and learned how to make quality plots.

Project 3 — Extracting data from the telescope log

Leader: Daniel Asmus (Fellow)

Similarly to Project 2, the participants used the telescope log files to monitor specific parameters of the SPectro-polarimetric High-contrast Exoplanet REsearch instrument (SPHERE), the Fibre Large Array Multi-Element Spectrograph (FLAMES), and the VIsible Multi-Object Spectrograph (VIMOS) in order to check the performance of the instruments at startup or the efficiency of acquisition templates. They learned how to read a large-volume text file, extract information, plot and use shell commands in Python.

Project 4 — Plotting the evolution of the Strehl ratio and atmospheric parameters using SPHERE adaptive optics data

Leader: Julien Milli (AO System Scientist)

In this group, the participants were invited to analyse the adaptive optics (AO) parameters from a SPHERE observation. They had to read the parameters from a FITS table, save them in a text file, and make quality plots (Figure 3). Advanced participants could also correlate the performance with atmospheric parameters by characterising the trends between Strehl ratio, star magnitude and coherence time. The conclusion of this project was that the Strehl ratio is sensitive to a combination of seeing and coherence time.

Project 5 — Centre the reference stars on FLAMES

Leader: Jorge Lillo-Box (Fellow)

During acquisition, three or four reference stars must be centred onto a bundle of fibres to guarantee good centring of the science targets. This advanced project aimed at automating this procedure. The participants learned how to make polar plots, retrieve coordinates by clicking on the plot and apply Bayesian analysis to find the centre of each star; they finally calculated the offset and rotation that should be applied for good centring.

Project 6 — Reading and inspecting data using *pandas*

Leader: Ignacio Toledo (ALMA Data Analyst)

Weather conditions from Paranal are available on the ESO webpage[5] and anyone can analyse their evolution and correlations. In this project the participants were invited to explore a very large text file with observing conditions of the last 16 years in Paranal using the Python module *pandas*[6] to retrieve and manage information, and the module *seaborn*[7] for graphic inspection of trends. Figure 4 shows that, for good seeing conditions (< 0.8 arcseconds), there is a range of possible coherence time values, all suitable for AO corrections on SPHERE and NACO for example, in agreement with Figure 3.

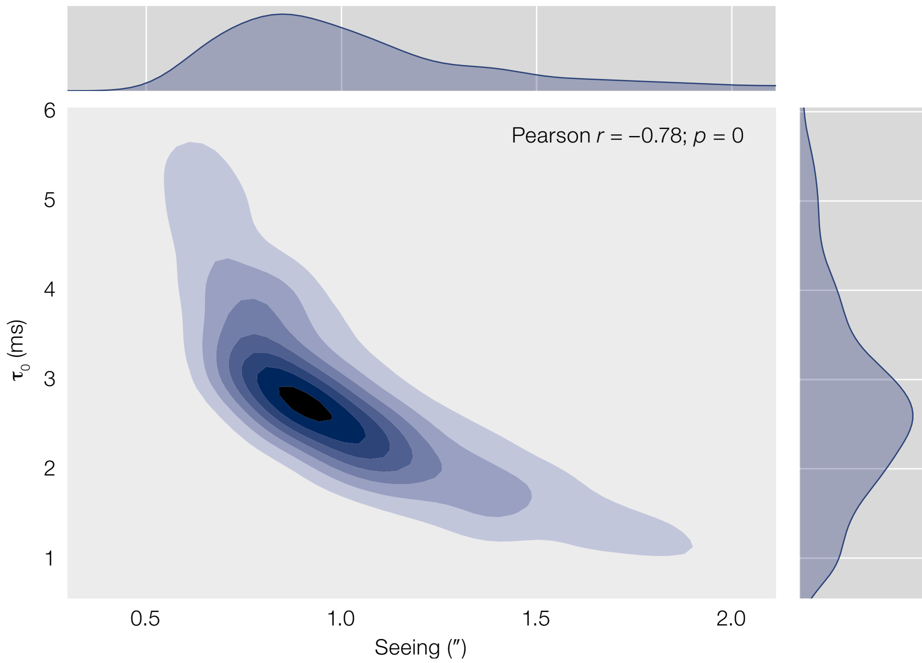


Figure 4. Relation between coherence time (τ_0) and Differential Image Motion Monitor (DIMM) seeing during January 2016 at Paranal as analysed in Project 6.

Feedback and next workshops

After the workshop we sent a feedback form to the participants to gather their reactions to this pilot Boot Camp. On a scale of 1 to 5 where 1 is maximum, 50 % of the answers gave an overall grade 1 for the event and its length at two full days. The quality of morning classes received grades 2 and 3 in 70 % of the answers. The quality of the afternoon projects received grades 1 and 2 in 75 % of the answers. These results confirm our expectations that hands-on activities are the best way to go. Based on the comments and grades we have decided to continue with this style of training project, and we now know where to improve.

The big challenge of this event was mixing participants with different backgrounds and with different levels of Python knowledge. We proposed that the participants should study the basics of Python using the CodeCademy[8] platform and arrive at the Python Boot Camp with at least the same basic level. From this starting point, all participants learned something new and useful. More advanced participants contributed different points of view on how to solve a given task, which highlighted the flexibility of Python.

Most of the participants reached and acknowledged the main goal of this workshop, and can now progress autonomously by self-learning, using web sources and the PyCoffee material. All of them left the event with Python scripts working on their computers and knowing how to edit and tune them for their own scientific or operational activities. Among the poll answers some people felt that the next run(s) of the Boot Camp should focus on some specific subjects, rather than cover a range of topics.

Finally, 100 % of the respondees agreed that we should continue the event. They also said we should keep the mix of people from different ESO and ALMA departments, as long as we remain a small event with around 30 participants and 10 trainers so as to be efficient during the hands-on activities and interactions. The majority of respondees agreed with maintaining the ESO Python Boot Camp as an internal training workshop for the moment. ESO and ALMA personnel change very often, and we depend on them as trainers. Therefore, we cannot offer an official training session on Python for the external community. Nevertheless, this event proved to be very efficient in terms of sharing knowledge that is already present among our colleagues. We can recommend this type of initiative to other research institutes in astronomy. If you are struggling with a task, you might have an expert next door willing to share his/her knowledge!

Acknowledgements

We thank all the teachers and lecturers for their contribution to this bootcamp.

Links

1 ESO PyCoffee: www.sc.eso.org/~bdias/pycoffee/. Managed by Bruno Dias, Julien Milli, and Callum Bellhouse
2 Berkeley Python Boot Camp: https://sites.google.com/site/pythonbootcamp/
3 NASA GSFC Python Boot Camp: https://asd.gsfc.nasa.gov/conferences/pythonbootcamp/2016/
4 IAG-USP Python Boot Camp: http://iagpyboot.wixsite.com/pbc2017
5 Paranal Ambient Query Forms: http://archive.eso.org/cms/eso-data/ambient-conditions/paranal-ambient-query-forms.html
6 Python Data Analysis Library *pandas*: http://pandas.pydata.org
7 seaborn statistical data visualisation: http://seaborn.pydata.org
8 CodeCademy: https://www.codecademy.com

DOI: doi.org/10.18727/0722-6691/5010

Fellows at ESO

Agnieszka Sybilska

I've been interested in learning about the Earth and beyond for as long as I can remember – at least since I received a children's cosmos encyclopedia at the age of seven. I remember telling everyone around that a teaspoon of matter from a black hole would weigh 100 million tons — I was fortunate enough to have an encouraging family who wanted to listen!

Having said that, nothing extraordinary happened between then and my high school years, other than that I was always curious to read and learn more and was fascinated by stories of planets, distant stars and galaxies. I majored in mathematics and physics in high school and took a first-year physics laboratory course at the local university, but there was little to no astronomy in it. There have been other "loves" in my life and, after finishing high school, I first went to study English philology and linguistics and only when I was in my third year in college, did I decide to start on an astronomy major as well. Doing the two simultaneously was admittedly challenging (imagine close to 50 course hours a week at three different locations in the city), but in the end I managed to obtain two Masters degrees after a total of seven years.

What has played a crucial role in my choosing a career in science, as opposed to humanities, was definitely an opportunity I got in 2008 to work as a Summer Research Assistant at the Space Telescope Science Institute (STScI) in Baltimore. Working at the STScI with Roeland van der Marel, Alessandra Aloisi and Aaron Grocholski on Hubble Space Telescope (HST) Wide Field and Planetary Camera 2 (WFPC2) data of nearby starburst galaxies was the opportunity that allowed me, for the first time, to see world-class science being done. I was really encouraged by the very positive attitude towards budding scientists like myself, which certainly gave me the motivation to continue in the field. The work I did at STScI evolved into a Masters thesis and certainly served as an excellent springboard to a PhD in astrophysics which I started in 2009 at the Instituto de Astrofísica de Canarias in Tenerife, Spain.


Agnieszka Sybilska

There I was a principal investigator of a project devoted to 3D spectroscopic imaging of dwarf early-type galaxies, the first of its kind for low-mass systems. I worked with Jesus Falcón-Barroso and Glenn van de Ven (Max Planck Institut für Astronomie, Germany) and we looked in particular at the kinematic and dynamical properties of our dwarfs. I got to experience first-hand all the steps of project development: from proposal writing, to preparing observing runs and then carrying out observations at the Observatorio del Roque de los Muchachos in La Palma, through to the reduction and analysis of the data and publishing of the results.

I moved to Germany a few months after finishing my PhD in June 2014, having worked on a Space Situational Awareness project for the European Space Agency (ESA) in between. Two months of an intensive language course in Munich went by and I was ready to go back to doing science full-time. My current work involves looking at both real and simulated galaxies to better understand the importance of the local environment on their evolution. As for the former, my main focus is on stellar populations and star formation histories of early-types, from dwarfs to giants. I also look at the evolution of simulated late-type galaxies in a cluster-like environment to follow the formation of their substructures.

At ESO I really enjoy the independence and being able to pursue my own research line. Working here has also given me a unique opportunity to experience first-hand the forefront of European astronomical research. Among other things, I got a chance to help as a scientific assistant to the ESO Observing Programmes Committee, which is enormously useful for better understanding the time allocation process and, hopefully, being able to write better proposals in the future (observing or otherwise). I've joked a number of times that when you're at ESO you don't have to travel to be up to date with the latest developments in the field — it's happening right here. While an exaggeration of course, the sheer number of conferences/workshops/symposia and numerous talks can make your head spin — just be careful not to make your goal attending all of them!

I'm a keen hiker and it somehow happened that I've always picked places to live abundant with magnificent hiking trails. This also nicely combines with my other hobby — landscape photography. I have never abandoned my linguistic interests and could say that learning new languages when starting a new job was almost as exciting as the job itself! Thanks to my astronomy adventures I now speak almost fluent Spanish and very good German. I've always found new challenges exciting and so as my family and I move to Poland in a few months, I'm very much looking forward to starting a job in a new field, working on precise astrometry in the context of ESA space surveillance and tracking activities.

Annalisa De Cia

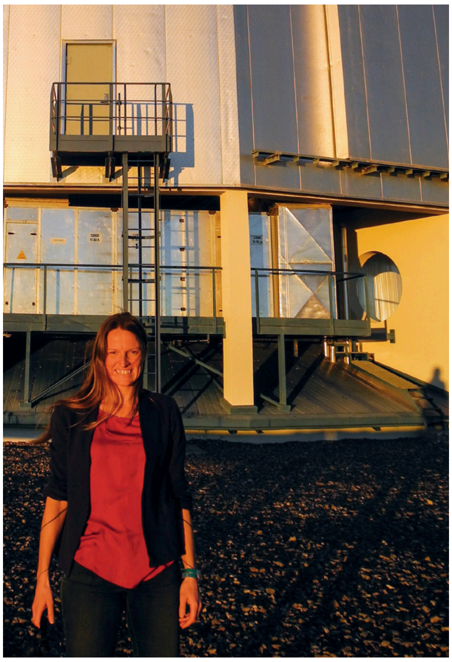
I grew up in a small town in northern Italy, surrounded by the Dolomite mountains and stunning landscapes. As a kid, I would follow my father's adventures as a paraglider pilot, and soon became fascinated by flying machines. My dream back then was to become a fighter-jet pilot, until I realised I was not really up for the army, nor for wars. But instead I loved science! At junior-high school I had a brilliant teacher and great facilities for all sorts of experiments — in electronics, optics, chemistry and biology. We would make field trips with experts in geology, and astronomy too. So I had no doubt that I would enroll in a science high school later. Soon I learned to have fun with mathematics and physics, and became more and more curious about how things work in the Universe.

The University of Bologna was my next step, where I got both Bachelor and Masters Degrees in Astronomy and Astrophysics. As part of my Masters, I spent almost a year at the University of Calgary, Canada. Back in Italy for my Masters thesis, I worked at the Astrophysics Institute (INAF/IASF) on the X-ray properties of a low-luminosity active galactic nucleus. While writing my thesis, I remember receiving an email regarding a PhD project on even more energetic and mysterious phenomena, gamma-ray bursts (GRBs), and their environments. And in Iceland. Poyekhali!*

Without hesitation, I took up the challenge, and set off on a new adventure. This was in 2008. The Centre for Astrophysics and Cosmology, University of Iceland, was a small but warm and stimulating astronomy group, which nurtured my scientific growth and also encouraged my independence by supporting visits and extended projects abroad with my external collaborators, such as at the Dark Cosmology Centre (Denmark), ESO in Chile and the University of Leicester (UK). My PhD years went by excitingly between science, aeroplanes and volcanic eruptions. I am still dreaming about the tremendous and exotic beauty of Icelandic nature.

During a conference in Nikko, Japan, I had learned to appreciate the scientific excellence of the Experimental Astrophysics Group of the Weizmann Institute of Science, Israel. So the science call, and (literally) favourable winds, took me south, to the opposite side of Europe. At Weizmann, I was introduced to the world of supernovae (SNe), and became part of a very active and cutting-edge supernova survey, the Palomar Transient

* Russian for "Let's go!", Yuri Gagarin, 1961



Annalisa De Cia

Factory. In particular, I started to work on superluminous supernovae (SLSNe), the most luminous SNe in the Universe, whose origin is a hot and still debated field. In the meantime, I became more and more fascinated by small distant galaxies, so faint as to elude normal observations. But we can use bright and distant background sources, such as quasars, GRBs, or SLSNe, to probe their gas properties in incomparable detail. In particular, I started to study the metals and dust within these distant systems, also known as Damped Lyman-α Absorbers (DLAs). The Middle East revealed itself as a very intriguing land, with an impressive historical heritage. But unfortunately with a complex and painful military and political struggle continuing.

In time, I developed a strong European feeling, and so I decided to move to a major astronomical organisation in Europe. I started at ESO as a fellow in September 2015, and immediately found myself loving the place, and being involved in observational and scientific activities, such as the "Gas Matters" club, which my colleagues and I founded to bring the Garching community together and discuss the multi-phase gas inside and outside galaxies. Scientifically, I have just published an extensive work (De Cia et al. 2016, A&A 596, A97) in which, for the first time, the chemical properties of the gas in the Galaxy and in distant galaxies were characterised in a unified picture. In particular, we derived the properties of the dust and the dust-corrected metallicity in the interstellar medium.

While I have used Very Large Telescope (VLT) observations for my science, I now have the opportunity to be a night astronomer on Paranal. As an ESO fellow, I am observing with Kueyen (Unit Telescope 2), driving the UV-Visual Echelle Spectrograph (UVES), the Fibre Large Array Multi Element Spectrograph (FLAMES) and the X-shooter spectrograph through their diverse science objectives, and learning more deeply the science operations at the Observatory, appreciating the excellence of these world-leading facilities, and participating in ensuring that the observations run smoothly and efficiently, thereby enabling the best science from the collected data. Enjoying a red sunset at the platform, watching the Sun melting into the clouds over the Andes (always hoping for a green flash) and the VLT showing its majesty, I feel lucky. None of this would have been possible without the many brilliant people who guided or inspired me through my journey. I have not named any of them here, but I am grateful to every single one of them. The journey is not over, and I am looking forward to what will be next! And I hope that science will continue to drive my dreams.

Jorge Lillo Box

Astronomy, with its link to philosophy, is probably one of the oldest sciences in the history of human beings. Our current job is nothing but a technological improvement and knowledge accumulation over the centuries, building on what the Mayas did in Central America, what the philosophers did in ancient Greece, what Hypatia and her disciples did in Alexandria, what the Rapa Nui did in Easter Island, etc. Nothing more, nothing less.

Becoming an astronomer is a long journey, and many different paths can lead to this final goal. I am pretty sure each of us has a different story in answer to the question "How did I become an

Jorge Lillo Box

astronomer". My story is not really a fancy one, it is just my story. Apparently, when I was a child, with very poor drawing and painting skills, I liked to draw stars in all the school paintings. This passion, however, was hidden in my brain for years, just waiting for the appropriate moment to come out. For a long time I thought about becoming a mathematician and teaching maths, because I really liked the feeling of solving problems and logic games. Discovering the mathematics behind the tick-tack-toe grid game, for instance, was one of those moments when your brain wakes up after years of being in passive mode and starts asking for more and more challenges. This was just one year before I started my pure physics course at the high school. And that was really the critical turning point.

I had the luck to have an extremely experienced, motivated, encouraging, and great physics and chemistry teacher. By just using chalk and the blackboard, he was able to open our minds, our brains, and, last but not least, our interest in answering the question "Why?". Why do things happen as they do in nature? What are the forces governing our world? Then in the same year I skipped my first class at high school to see the 2004 transit of Venus using binoculars with solar filters attached. So, during the last two years of high school, this hidden passion for astronomy that had been there since I was a child, suddenly came out, and I finally said these words to my parents: "Mom, Dad, I want to become an astronomer".

After my degree, I specialised in a hot topic for my PhD: exoplanets in the context of the Kepler mission. My advisor, David Barrado, provided me with the unique and special opportunity to do my doctorate at the Center for Astrobiology in Madrid, and he guided me through this completely new world of astronomical research. From my point of view, this is exactly what I needed, just guiding. During life we are taught many concepts and assumed facts that are, apparently, irrefutable. Freedom of thought is usually avoided (or forgotten) during the learning process at school and university. However, during my PhD I had the necessary freedom to start thinking by myself, to have my own ideas, to start questioning what I was taught. So, this was another of those moments, mentioned before, when my brain woke up again and started exploring new ways of thinking, looking for new challenges.

And this is how I accomplished one of my dreams. Even though thousands of planets have already been discovered, one of them will always be very special to me. This is Kepler-91b, my first discovered planet. This hot Jupiter was the first planet confirmed to transit a giant star and the closest planet to an evolved host ascending the red giant branch, orbiting at just 2.3 stellar radii around the star and the only planet known around a giant star closer than 0.5 au at that time. A handful of planets of this kind were discovered afterwards and they proved to be key to our understanding of the evolution of planetary systems once the star leaves the main sequence.

In the last stages of my PhD, I had another of those "brain please wake up" moments. Suddenly, I found myself applying for postdoc positions and fellowships around the world, all of them requiring a "Research Plan". So, this was an excellent opportunity to be creative, to try breaking the established rules of what we think can and cannot exist in the Universe and to face impossible challenges. From my point of view, this is how we push science to the next level, and so I proposed the TROY project.

ESO gave me a great and unique opportunity not only to develop this project but also to learn, contribute and be part of one of the greatest astronomical facilities in the world, as part of the Scientific Operations team of the Very Large Telescope at Paranal. I was assigned as support astronomer of the Moon (Kueyen in Mapuche language or simply Unit Telescope 2), instrument fellow of X-shooter and the instrument fellow for the forthcoming Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO). The new capabilities and opportunities that ESPRESSO will bring for the exoplanet community in particular (but also for cosmology and extragalactic studies) make it a complete challenge from both the scientific and the technological point of view. It is still difficult for me to understand that we will be able to measure the radial component of the velocity of a star located hundreds of parsecs away with a precision better than the speed of a walking turtle. Just amazing!

I am looking forward to seeing ESPRESSO in operation and the new space- and ground-based facilities coming in the near future (CHaracterising ExOPlanet Satellite [CHEOPS], PLAnetary Transits and Oscillations of stars [PLATO], the James Webb Space Telescope [JWST], etc.), as well as to develop my own ambitious scientific projects. All this is contributing to our understanding of the place in which we live, the Universe we inhabit. Just continuing what our ancestors did years, centuries and millennia ago. Nothing more, nothing less!

Personnel Movements

Arrivals (1 January–31 March 2017)

Europe	
Czepanski, Jasna (DE)	Administrative Assistant
Flörs, Andreas (DE)	Student
François, Mylène (FR)	Administrative and Document Management Assistant
George, Elizabeth (US)	Detector Engineer
Guglielmetti, Fabrizia (IT)	ALMA Pipeline Processing Analyst
Harrison, Christopher (UK)	Fellow
Haug, Marcus (DE)	Cryogenic Systems Engineer
Lelli, Federico (IT)	Fellow
Lucchesi, Romain (FR)	Student
Montesino Pouzols, Federico (ES)	Software Engineer
Müller, Eric (DE)	Instrumentation Engineer
Nogueras Lara, Francisco (ES)	Student

Chile	
Aguilar, Max (CL)	Hospitality Operations Supervisor
Carcamo, Carolina (CL)	Procurement Officer
Cardenas, Mauricio (CL)	Telescope Instruments Operator
Ciechanowicz, Miroslaw (PL)	Senior Electronics Engineer
Muñoz, Miguel Patricio (CL)	Electronics Technician
Muñoz, Ingeborg (CL)	Unix-Database Specialist
Rojas, Alejandra (CL)	Student
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Guzman, Lizette (MX)	Fellow


ESO/S. Fandango

View of the ALMA Operations Site (AOS) from inside the AOS Technical Building. See Picture of the Week potw1642 for more information.

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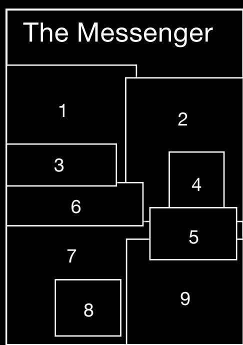
1. The Large Magellanic Cloud (LMC) before explosion of SN 1987A; ESO 1-metre Schmidt optical image.
2. SN 1987A close to its peak brightness; ESO Schmidt image in optical.
3. Optical spectral evolution of SN 1987A over first 110 days; sequence with Bochum telescope (from Hanuschik & Thimm, 1990, A&A, 231, 77).
4. Light echoes around SN 1987A; NTT Hα image from 1992.
5. ISAAC broad slit spectrum centred on He I 1.083 µm line from 1999.
6. UVES spectrum centred on Hα taken in 1999.
7. Early NTT [N II] 6583 Å image of SN 1987A from 1991.
8. NACO near-infrared adaptive optics image from 2006.
9. Composite sub-mm (ALMA, in red), visible light (Hubble Space Telecope in green) and Chandra X-ray image (in blue) of the current appearance, and released for the 30th anniversary. See ESO Picture of the Week potw1709 for details.



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