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ESPRESSO Science Verification
The VLT-FLAMES Tarantula Survey
NGTS – Uncovering New Worlds with Ultra-Precise Photometry
Magellanic Clouds – Historical Perspectives & A View from VMC, Gaia and Beyond

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Contents

Instrumentation

Astronomical Science

Astronomical News

Front cover: This image of the Large Magellanic Cloud, obtained by the VISTA telescope as part of the ESO Public Survey called the VISTA Magellanic Clouds Survey (VMC), reveals the contents of one of our nearest galactic neighbours in unprecedented detail. The VMC allows astronomers to trace stellar evolution, galactic dynamics and stellar variability in different environments.

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ESPRESSO Science Verification

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ESPRESSO Science Verification took place at the end of August and the beginning of September 2019. It was spread over two visitor-mode nights, requiring seven hours of observations taken in service mode. The weather conditions (strong winds and poor seeing conditions) and some telescope problems (failure of guide cameras) hampered the first two nights and additional time was granted to finish the top-ranked programmes. In response to the call for ESPRESSO science verification, 16 proposals were submitted, 10 of which were scheduled for a total of 25 hours of observations. A slight oversubscription of the available time was planned to allow for the prevailing atmospheric conditions. The seven top-ranked programmes were fully completed.

Proposal solicitation and submission

ESPRESSO is offered with one VLT Unit Telescope (1-UT mode) or with all 4 Unit Telescopes (4-UT mode) combined. ESPRESSO has already been offered in 1-UT mode since Period 102 (October 2018) and a call for ESPRESSO science verification proposals with the 4 UTs combined was issued on 14 June 2019[1,2] offering 2 observing nights. Alongside the call, the ESPRESSO science verification webpage[3] was launched and 16 proposals were received by the deadline on 5 July 2019, requesting a total of 32.3 hours.

The science verification team ranked the proposals according to scientific merit. Ten projects were selected for a total of 25 hours of execution time, which resulted in an oversubscription of the available time by about 25%. Proposers were informed of the outcome of the selection on 22 July 2019 in time to meet the Phase 2 deadline on 31 July.

The proposed science cases covered a wide range of topics, including the observation of the most massive star in a distant dwarf galaxy, the detection of water in an outgassing comet from the main asteroid belt, the characterisation of an exoplanet atmosphere during a transit, measuring the chemical composition of a turnoff star in a globular cluster, an attempt to measure the fine-structure constant at high redshift, observations of potential stimulated (laser) emission in a distant galaxy, the first measurement of the ^{12}C:^{13}C ratio in a low-metallicity damped Lyman-α system, and the detection of ^{6}Li in a star in the SMC.

Observations

The ESPRESSO science verification nights were scheduled on 26 and 27 August 2019. The first night was severely affected by inclement weather (high winds), which resulted initially in pointing restrictions and subsequently closure of the domes. The second night started with pointing restrictions and a seeing of 1.5 to 2 arcseconds. The acquisitions proved to be more time consuming than expected owing to the faintness of the science targets. Owing to a technical problem, one UT could not be used, and so the observations continued with three telescopes, the exposure times being adjusted accordingly for some programmes. Despite these problems four programmes could be completed. Owing to the significant loss of observing time the observatory granted another 7 hours of observing time in early September. Data for three additional programmes could be acquired under excellent conditions over the following nights so that 7 out of 10 scheduled programmes could be completed. The ESPRESSO science verification page provides information on the completed programmes and links to the archived data.

Archive and data processing

All raw data are publicly available through the ESO science archive. The ESPRESSO science verification webpage has been updated with direct links to the raw data in the archive. Pipeline-reduced data (version 1.4.2) were also provided, and are linked from the ESPRESSO science verification webpage. The current ESPRESSO pipeline release is version 2.2.1[4]. Some of the data presented below were reduced with the ESO Data Reduction Software (DRS) (Sosnowska et al., 2015) and analysed with the Data Analysis Software (DAS) specifically developed for ESPRESSO (Cupani et al., 2019).

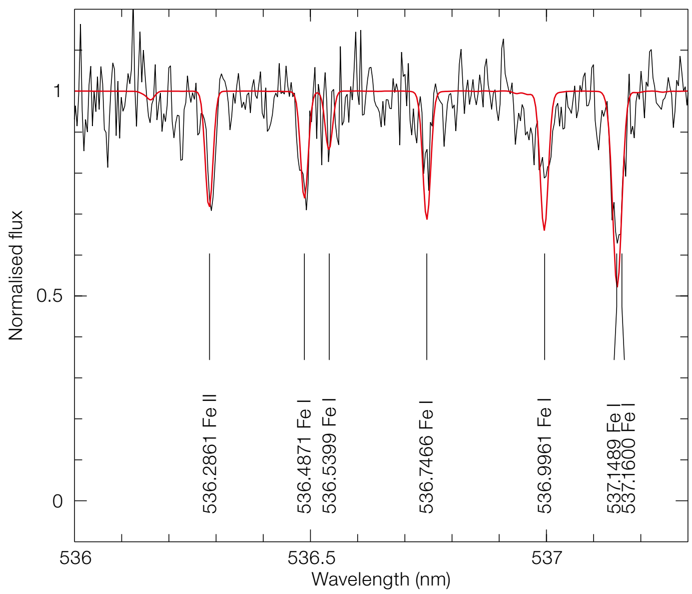

Figure 1. Details of the ESPRESSO spectrum of a blue straggler in the globular cluster Pal12 compared to the MyGIsFoS (Sbordone et al., 2014) analysis. The best fitting synthetic spectrum is shown in red.

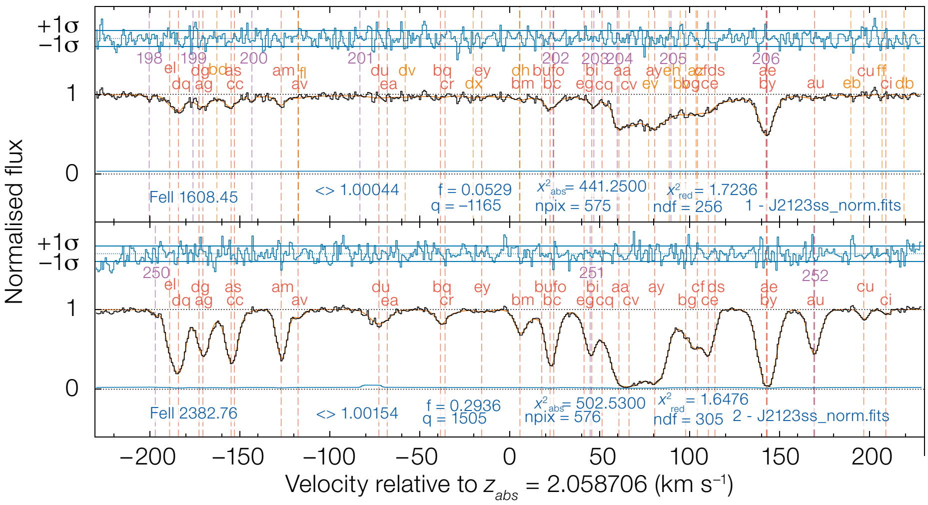

Figure 2. Details of the ESPRESSO spectrum of a sub-damped Lyman-α system. Many suitable transitions are detected in an absorption complex spanning about 400 km s^{-1}. The Fe II transitions falling within the spectral range covered by the 4-UT ESPRESSO data include lines at 1608, 2344, 2374, 2383 and 2600 Å. The figure shows two of these, 1608 Å and 2383 Å. Illustrated along with the 1608-Å profiles are the interesting broad CIV 1550-Å features modelled by Hamann et al. (2011) as outflows from the quasar. Since wavelength calibration makes use of the laser frequency comb, one of the major sources of systematic errors in this sort of study is eliminated. Preliminary results, solving for α, indicate an overall error budget at around the 10^{-6} level, making this one of the most precise measurements of α to date.

Science results

Chemical composition of an extragalactic turnoff star

A blue straggler in the globular cluster Pal 12 was observed. This solar-mass star is close to the main-sequence turnoff of this globular cluster in the Sagittarius dwarf galaxy. It represents the best chance to observe a bona fide extragalactic low-mass star with known age and metallicity. A debate is ongoing as to whether blue stragglers are formed by collision or by fusion of two stars and it should be possible to distinguish between these possibilities by measuring the Li abundance, which is expected to be around A(Li) = 1.0 for collisions and fully depleted in the case of a merger.

This programme aimed to obtain abundances for a star of $V \approx 19.1$ to demonstrate the potential of the 4-UT mode for faint star spectroscopy. Sky subtraction is essential to derive precise abundances at these magnitudes. However, the sky spectra collected on fibre B were found to be contaminated by another source. This is a problem in crowded fields: during one exposure, the field rotates and the sky fibres draw an arc in the sky so they may get contaminated by nearby sources. The geometry of each telescope is different, so it may happen that only one telescope contributes to the contamination. Thanks to this observation, a tool has been now added in the finding charts generator that shows the partial circle "observed" by the ESPRESSO sky fibre, so the user can check that no objects overlap with it.

The signal-to-noise ratio per integrated pixel in the fully reduced data is ~ 23 in the Li 6708-Å region, which is adequate to derive abundances for several elements (see Figure 1). Unfortunately, the upper limit on the Li abundance is not low enough to decide on the blue straggler mechanism formation, but other element abundances and their comparison with the abundances obtained in giants of the same cluster will nevertheless provide interesting results.

Disappearance of a luminous blue variable

Massive stars in low-metallicity environments are very interesting and may be linked to different types of supernovae. The metal-poor dwarf galaxy PHL 293B hosted a luminous blue variable star, for which ESPRESSO was supposed to provide a detailed spectral analysis. The proposers hoped to determine luminosity, effective temperature, surface abundances and wind parameters for this object in a low-metallicity environment. As it turned out the signature of the luminous blue variable — broad hydrogen lines from the wind — had disappeared at the time of the observations in August

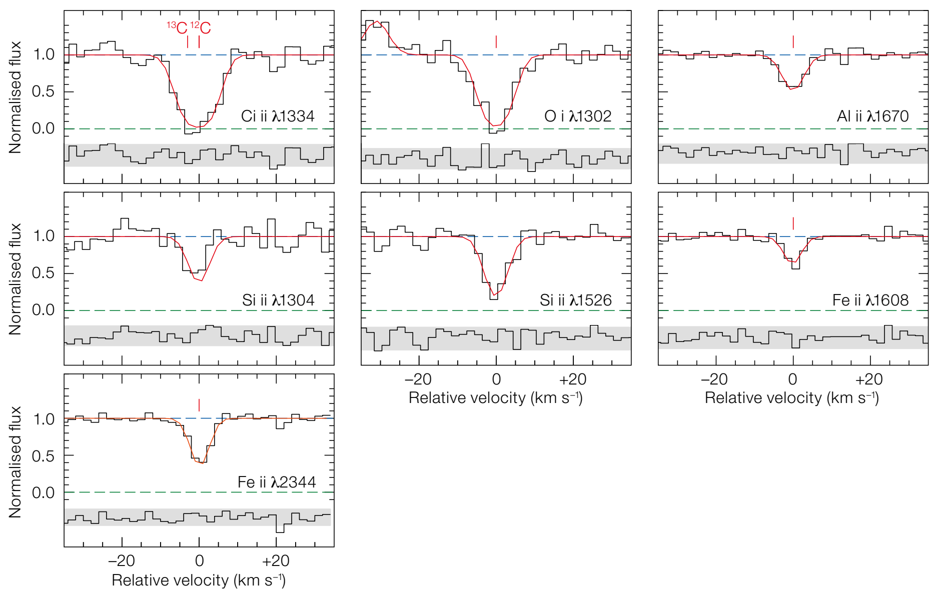

Figure 3. Line fits to various absorption lines in the DLA (z = 2.34) towards J0035-0918. The rest-frame wavelengths are indicated by red tick marks. From Welsh et al. (2020).

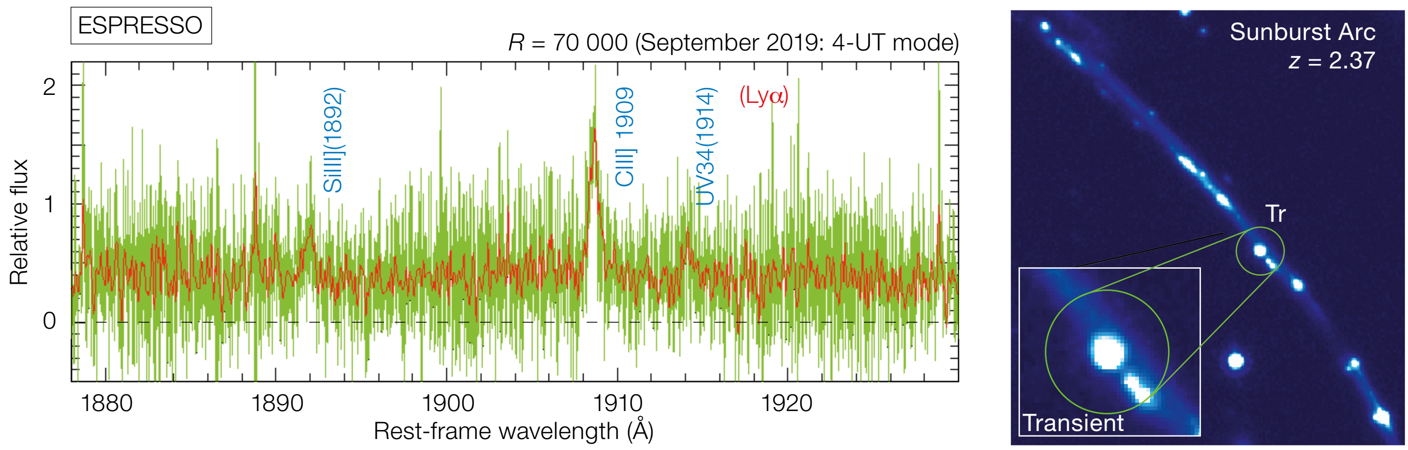

Figure 4. The left panel shows the one-dimensional spectrum obtained with ESPRESSO (green, R = 70 000) and the smoothed version (red, R = 7000). Three lines are indicated, SiIII]1892, CIII]1909 and the faint fluorescent iron line at 1914 Å as part of a group of lines known as UV34. The 1914-Å line is generated by Lyman-α pumping radiation. The right panel displays the HST ACS/F814W image of the lensed arc, with the inset zooming in on the region of the transient Tr observed with ESPRESSO (the green circle corresponds to 1 arcsecond in diameter), while the boxes are 9 arcseconds across. From Vanzella et al. (2020b).

2019 (Allan et al., 2020). A quick double-check with X-shooter was requested and confirmed the disappearance of the luminous blue variable features. This led to the conclusion that the star was in a luminous blue variable outburst in the first decade of this century but that the outburst must have ended after 2011, as deduced from archival data. This was the first time such an event had been found in a low-metallicity galaxy. Possible interpretations include that, after the eruption, the star shifted to a higher temperature, that it suffers dust obscuration or that the star collapsed directly to a black hole without a supernova display. High-resolution imaging to determine the current brightness of the star should provide information that will make it possible to decide between these possibilities.

Fundamental constants

One of ESPRESSO's key scientific goals is to measure the variation of fundamental constants, and if they change in time or spatially. A sub-damped-Lyman-α (DLA) system at z = 2.059 shows well-separated absorption components. The individual components appear strong yet unsaturated and are ideal for a measurement of $\Delta\alpha/\alpha$ promising to provide a strong new constraint on any change. Figure 2 shows part of the high-signal-to-noise spectrum around two Fe absorption lines.

$^{12}C/^{13}C$ molecular ratio at high redshift

The formation of elements proceeds via stellar enrichments. Depending on the enrichment source, different values of the ratio of the two carbon isotopes ^{12}C and ^{13}C are expected. For example, supernovae from massive stars of the first generation of stars (Population III) will mostly produce ^{12}C, while evolved stars on the asymptotic giant branch (a later Population II) will have a higher fraction of ^{13}C. The isotopic wavelength shift for two carbon transitions at 1334 Å is only 0.013 Å, corresponding to a relative velocity shift of 2.99 km s^{-1}. To measure such a tiny wavelength offset, very high spectral resolution and a high signal-to-noise ratio are required — an ideal case for ESPRESSO combining the light of all four UTs. Figure 3 (from Welsh et al., 2020) shows absorption lines from a damped-Lyman-α system at a redshift z = 2.34. This system was chosen because it appears to be one of the most pristine gas clouds known at high redshift. The individual lines are well fitted by models of a single line. The ratio $^{12}C/^{13}C$ is best fitted with $\log(^{12}C/^{13}C) = 1.15 \pm 0.65$ and a 2σ upper limit for this ratio was found to be $\log(^{12}C/^{13}C) > 0.37$. This ratio is not quite tight enough to distinguish between the possible enrichment models. Interestingly, the star formation can be determined to have started only about 1 Gyr after reionisation of the Universe and star formation was quenched by heating of the interstellar medium. The data were of sufficiently high signal-to-noise to provide an upper limit on the variation of the fine-structure constant, one of the main scientific goals of ESPRESSO.

Space foam

Space is generally assumed to be a continuum, but some models of quantum gravity predict that it may have a "frothy" structure. Such models involve a change in the characteristics of an emitted photon — for example, its energy — as it travels through space. A monochromatic light source would gradually disperse as a result of space-time fluctuations. Since these effects are predicted to be tiny, long distances must be probed. ESPRESSO observations were used to investigate the narrow Fe II 1608-Å line in a DLA at z = 2.34, corresponding to a comoving distance of 5.8 Gpc (Cooke et al., 2020). The critical measurement is the broadening of the line caused by space foam effects. For the line broadening, the thermal energy dominates and hence a line from an element with a high atomic number is favoured. At the same time, the effect depends on the ratio between distance and wavelength, and the shortest available wavelength of a heavy element is best suited to this measurement — hence the choice of the Fe II ultraviolet line. The limits derived from the high signal-to-noise ESPRESSO spectrum are promising but not yet competitive with imaging point sources at the highest observed energies.

Lensed transient at z = 2.37

ESPRESSO was used to observe a strongly lensed peculiar stellar transient at cosmological distance z = 2.37 hosted in the highly magnified Sunburst arc (Vanzella et al., 2020a; Rivera-Thorsen et al., 2019).

The target, indicated by the letters “Tr” in Figure 4, is very faint (around 21 magnitudes) for a high-resolution spectrograph and was observed at an airmass of 1.7. The wavelength-calibrated, sky-subtracted, optimally extracted spectra of the orders produced by the DRS were combined by the DAS into a spectrum of remarkable quality, in which the continuum is detected at a signal-to-noise around 3 (per resolution element) together with several emission lines at signal-to-noise around 3–10 (see Figure 4). The exact nature of the transient is still under investigation to determine where it may fit among the possible categories of supernovae (Vanzella et al., 2020b). Fluorescence emission from iron is detected as the result of possible interaction among the circumstellar material and the explosion event.

Summary

The capabilities of the ESPRESSO 4-UT mode have been amply demonstrated by the presented projects. Four refereed papers have already been published showcasing new results, and they demonstrate the scientific interest this new VLT facility fosters.

Acknowledgements

We received excellent support at the telescope from the Telescope and Instrument Operators. They accommodated additional science verification observations flexibly to conclude as many programmes as possible after the first night was lost to inclement weather. We would like to thank the following Principal Investigators who kindly provided the preliminary science verification results presented in this article: Luca Pasquini and Piercarlo Bonifacio, José Groh, Ryan Cooke and Louise Welsh, Eros Vanzella, and John Webb, Dinko Milakovic and Vincent Dumond.

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Links

[1] Science announcement of the ESPRESSO Science Verification: http://www.eso.org/sci/publications/announcements/sciann17215.html
[2] Announcement of the ESPRESSO Science Verification in the Science Newsletter: https://www.eso.org/sci/publications/newsletter/jun2019.html
[3] ESPRESSO Science Verification website: http://www.eso.org/sci/activities/vltsv/espressosv.html
[4] Latest ESPRESSO pipeline release: http://www.eso.org/sci/software/pipelines/espresso/espresso-pipe-recipes.html

Y. Beletsky (LCO)/ESO

A panorama of the VLT platform with distinctive red airglow visible overhead.

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An Era Comes to an End: The Legacy of LABOCA at APEX

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It was 13 years ago, in May 2007, when the Large APEX Bolometer Camera (LABOCA) was commissioned as a facility instrument on the APEX telescope at the 5100-m-high Llano de Chajnantor. This 870-μm bolometer camera, in combination with the high efficiency of APEX and the excellent atmospheric transmission at the site, has offered an unprecedented capability in mapping the submillimetre continuum emission in objects ranging from the Solar System and star-forming regions throughout the Galactic plane, to the most distant galaxies. As the operation of LABOCA is soon coming to an end to make space for a new array of continuum detectors, we present an overview of the challenges, lessons learned and science impact that it has generated. To date, LABOCA has produced the most papers of any APEX instrument and compares favourably with many VLT instruments.

Introduction

Continuum imaging at (sub)millimetre wavelengths provides unique information on the thermal dust emission from circumstellar discs (for example, Beckwith et al., 1990) and star-forming regions (for example, Motte, Andre & Neri, 1998). As these wavelengths probe the steep Rayleigh-Jeans slope of cold (< 100 K) dust emission, the observed flux density remains roughly similar from $z = 1$ to $z = 10$, which makes this wavelength regime ideal to select targets over half the age of the Universe. As the sensitivity depends on the bandwidth covered, bolometers have a major advantage over heterodyne instruments. After initial efforts using single bolometers (for example, Kreysa, 1985), several small arrays of bolometers came online in the 1990s: Submillimetre Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) in Hawai'i (Holland et al., 1999), Max Planck Millimeter BOlometer (MAMBO) on the IRAM 30-m telescope of Pico Veleta and SEST IMager Bolometer Array (SIMBA) on the SEST at La Silla in Chile (both Kreysa et al., 1999).

In the 1990s, SCUBA had just opened up the field of observational submillimetre cosmology by mapping massive clusters and the Hubble Deep Field (Smail et al., 1997; Hughes et al., 1998). Its main limitation was the small field of view and further progress was only possible by increasing the bolometer array sizes by an order of magnitude. This motivated the bolometer development group led by Ernst Kreysa at the Max Planck Institute for Radio Astronomy in Bonn (MPIfR), who had already provided the community with MAMBO, SIMBA and its line of predecessors, to build LABOCA (Siringo et al., 2009) for the new Atacama Pathfinder Experiment (APEX) 12-m submillimetre telescope as one of its main facility instruments (Güsten et al., 2006). With as many as 295 bolometers covering a circular field of 11.4 arcminutes, LABOCA would remain the largest submillimetre array till the SCUBA-2 instrument became available on the JCMT in 2012 (Holland et al., 2013). Being installed on APEX, LABOCA could also make optimal use of the excellent weather conditions on Chajnantor, where the 870-μm atmospheric window is observable for almost two-thirds of the available weather conditions (Otarola et al., 2019). In addition, seeing the same sky as ALMA optimised LABOCA's synergy as the ideal source finder for ALMA.

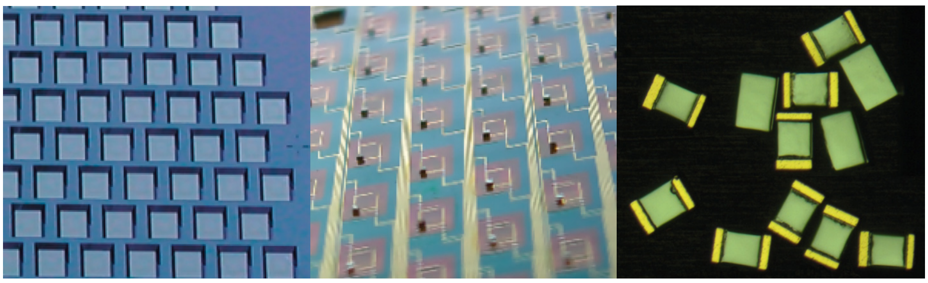

Figure 1. The LABOCA bolometer array consists of 295 semiconducting composite bolometers arranged in a hexagonal grid. The array is manufactured on a 10-cm single-crystal silicon wafer coated on both sides with a silicon-nitride film by thermal chemical vapour deposition. The wiring is created by microlithography of niobium and gold thin layers (left); one broken membrane is visible on the top left corner. On the opposite side of the wafer, 295 square cavities are etched into the silicon wafer by wet etching with potassium hydroxide, producing freestanding, unstructured silicon-nitride membranes of 400-nm thickness (middle). A very thin titanium layer is then sputtered onto the cavity side of the wafer to act as absorber for the submillimetre radiation. In a last step the thermistors are soldered to free-standing membranes with an indium alloy. The thermistors are brick shaped (right) but appear as small cubes on the membranes because of the viewing angle.

Figure 2. The image on the left shows APEX staff astronomer, Andreas Lundgren, in the process of refilling LABOCA. The transfer tube that is wrapped behind his back goes from a liquid helium dewar in the foreground to the helium tank in LABOCA, shown in the inset image in the upper left corner. The cryostat is shown from above in this inset. The image on the right shows Ernst Kreysa, the leader of the MPIfR bolometer group, together with the LABOCA cryostat in the Cassegrain cabin of the APEX telescope. At the time the picture was taken, the instrument PolKa was being installed.

Being faster than the sky

Observations of astronomical objects from ground-based telescopes at (sub)millimetre wavelengths require techniques to minimise disturbance from the Earth's atmosphere, which is seen by a bolometer as a fluctuating bright screen. The most widely used minimisation technique is to modulate the signal from the sky, usually by chopping with the secondary mirror between two close positions, ideally at a frequency higher than that of the sky fluctuations. Synchronous demodulation is then used to filter out the sky noise and extract the signal of astronomical interest. Mapping a region of the sky by scanning in the chopping direction will result in both a positive and a negative source signal separated by the chopping amplitude. A similar technique has been used with double horn receivers at centimetre wavelengths. Efficient algorithms have been developed to retrieve sources from double-beam maps (Emerson, Klein & Haslam, 1979). This method has also been used with bolometers.

The experience with MAMBO and SIMBA played an important role in the design of LABOCA. The new bolometer camera was intended from the beginning to be used in a fast scanning mode, to take full advantage of the fast-moving telescope (as an ALMA prototype) without using the chopping secondary. The design therefore required fast sampling of the bolometers' signals. Following the success of the MAMBO analogue-to-digital converter (ADC)-based backend, a new ABBA backend for LABOCA has been built, upgrading the scheme of the MAMBO one, which can sample up to 320 analogue channels in parallel up to 1000 Hz (see a detailed description by Siringo et al., 2009). The total power design has been optimised to make LABOCA capable of mapping the most diffuse emission of large extended sources. A detailed analysis of spatial filtering with an investigation of the Chamaeleon dark clouds by Belloche et al. (2011a,b) showed that the size of the structures that can be recovered is limited to about 5 arcminutes, i.e., half the array size.

During the commissioning of LABOCA, extensive tests and simulations were undertaken to determine the optimal scanning pattern. Lissajous patterns are often used at other (sub)millimetre telescopes to achieve good spatial sampling. However, they turned out to have a tendency to give greater weight to the edges of the map with less coverage in the centre. A new observing pattern was therefore created for fast scanning with APEX: by using strokes at constant velocity in polar coordinates it was possible to move the telescope along spiral patterns optimised to obtain maps with full spatial sampling and excellent coverage. For coverage of square degrees or more, rectangular on-the-fly maps turned out to be more efficient.

The lack of a readily available software package to reduce the data has been recognised as a major drawback of the fast scanning technique applied to MAMBO and SIMBA. For this reason, in parallel with the hardware development of LABOCA, a new data reduction software package was developed, called the Bolometer data Analysis package (BoA; Schuller, 2012), which is able to reduce data acquired with LABOCA in any of the possible observing modes; the package is mostly based on Python, and is open source, distributed under the GNU General Public License. In addition, the Comprehensive Reduction Utility for SHARC-2 package (CRUSH; Kovács, 2008) was adapted to handle LABOCA data.

The LABOCA detectors

The initial design of LABOCA considered using superconducting transition-edge sensors (TES) developed at the MPIfR in collaboration with the Institute for Photonics Technology of Jena (IPHT) and operated with a closed-cycle pulse-tube cryo-cooler (Jethava et al., 2008). However, the pressure to install LABOCA as quickly as possible led to the decision to stick with well-established semiconductor-based bolometers (neutron transmutation doped [NTD]-germanium thermistors, see below) in a liquid helium cooled "wet" cryostat to avoid problems with microphonics. While this inevitably led to some operational constraints (see the section on cryogenics below), it did allow

LABOCA to produce scientific results several years before other submillimetre instruments like Herschel and SCUBA-2 came online. The effort in designing and prototyping TES bolometers was not in vain: the new technology was used in the Submillimetre APEX Bolometer Camera, SABOCA (Siringo et al., 2010), a 37-element array for the 350-μm atmospheric window that was commissioned in 2008 as a facility instrument on APEX. SABOCA remained operational until 2015, when it was replaced by the ArTéMiS instrument covering both the 350- and 450-μm atmospheric windows (Talvard et al., 2018).

NTD thermistors for bolometer arrays need extremely tight control of the doping for uniform performance. The group under Eugene E. Haller at Lawrence Berkeley Laboratory (LBL) pioneered the use of NTD-germanium for this purpose, in cooperation with the MPIfR bolometer group (Palaio et al., 1983). When designing LABOCA, several crystals of NTD-Ge with different dopings were available to choose from. Optimal chip resistance is then determined only by temperature and geometry to match the noise properties of the silicon field-effect transistor amplifier. This was achieved by precision dicing at LBL, with boron low-noise contacts and gold coating for ease of soldering. The chips are finally polish-etched to remove noise producing surface states, which explains the rounded corners of the chips (Figure 1).

Tertiary optics with integrated polarimetry mode

The main task of the tertiary optics is to transport the beams from the Cassegrain focal plane to the final focal plane in the cryostat, while changing the focal ratio from *f*/8 to *f*/1.5. In order to satisfy the boundary conditions of the APEX C-Cabin, an optical solution was found with two Gaussian beam telescopes in series. This design has an ideal position for a reasonably sized reflective half-wave plate with a small angle of incidence near the common waist of the two telescopes. Three off-axis mirrors, two plane mirrors and a lens (the cryostat window) make up the tertiary optics. Unfolding the optical path at the plane mirrors would show that this solution still maintains one plane of symmetry. This property contributes to the diffraction-limited performance at 350 μm. Relaxing the wavelength to 870 μm and doing without the polarimetry mode would allow much simpler optics to be designed.

The polarimeter for LABOCA is an enhanced version of the Polarimeter für Bolometer Kameras (PolKa) developed at MPIfR between 2000 and 2004 as a plug-in instrument adding polarisation capabilities to any of the MPIfR bolometer arrays, at different wavelengths and on different telescopes (the 10-m Heinrich Hertz Telescope and the IRAM 30-m telescope). A complete description and some results are presented in Siringo et al. (2012).

The polarisation modulator used in PolKa is a rotating reflection-type half-wave plate. The reflection-type half-wave plate consists essentially of two parts: a wire-grid linear polariser and a plane mirror, held parallel to each other. By tuning the distance between the two parts, it is possible to introduce a controlled phase shift between the two components of the linear polarisation, because one is reflected by the wires and the other one by the mirror after a longer path.

PolKa for LABOCA was not yet available at the time of LABOCA's installation and commissioning — it was installed at the

Figure 3. LABOCA emission map of the Barnard 211/213 filament in Taurus (red emission) superposed on an optical DSS image of this region (background). Note the rich substructure shown by the LABOCA emission along this region, including multiple branches and condensations corresponding to dozens of small-scale fibres inside this filament.

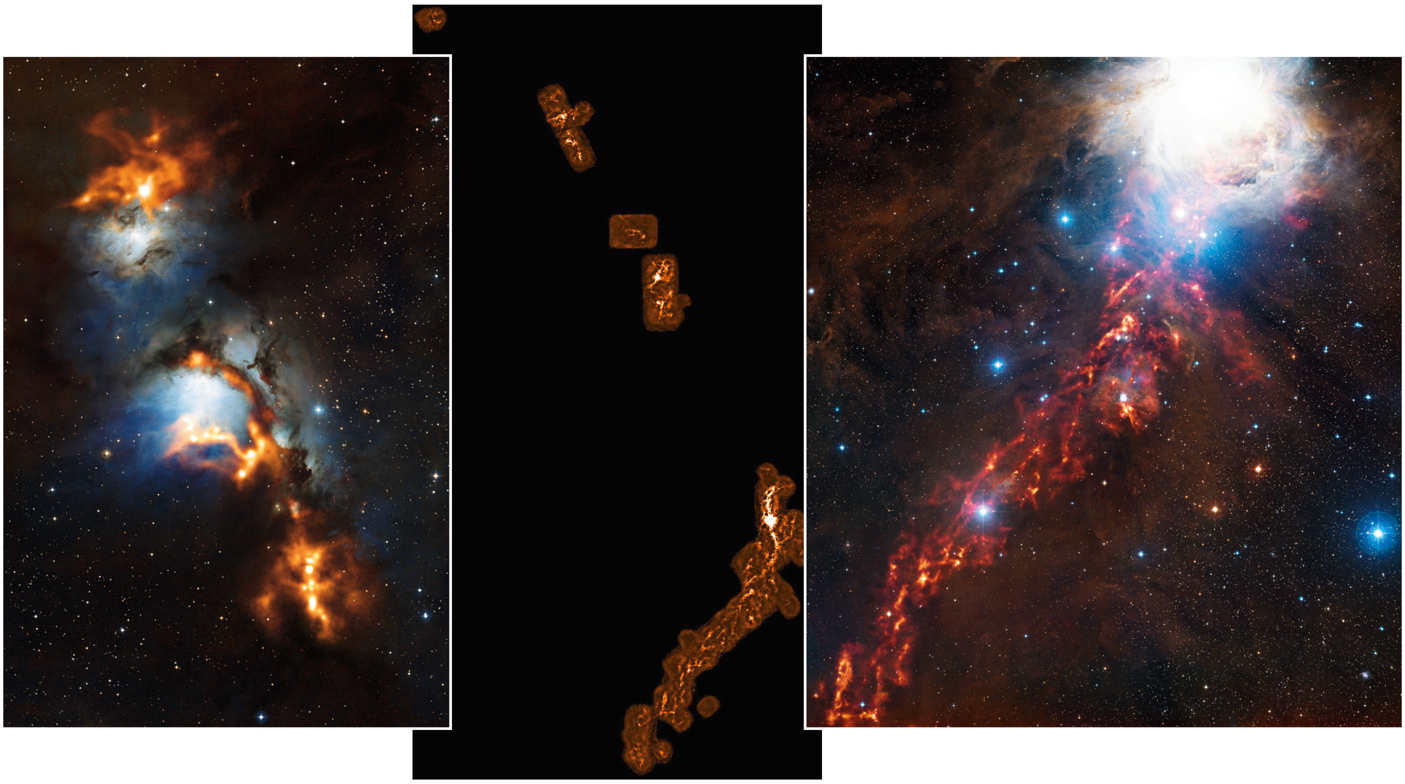

Figure 4. Middle: full extent of the Orion LABOCA survey, spanning almost 11 degrees north to south. The northern half covers prominent star-forming clumps in the Orion B giant molecular cloud (from north to south: L1622, NGC 2071 and NGC 2068, Ori B9, and NGC 2024 and NGC 2023 including the Horsehead Nebula). The southern half covers a major fraction of the Orion A giant molecular cloud, including the Integral-Shaped Filament with the Orion Nebula at its centre at the top, and the L1641 cloud further south. Left: zoom-in on the NGC 2071 and NGC 2068 area, with LABOCA dust emission shown in orange on top of a multicolour optical image (DSS). Right: close-up of the filamentary dust emission extending south-east of the Orion Nebula in the L1641 cloud.

end of 2009 as a permanent add-on available for use with LABOCA until the end of its operation. For polarimetry, one mirror was replaced by the reflection-type half-wave plate on its air bearing. When PolKa was not being used, only the delicate wire grid of the reflection-type half-wave plate had to be removed (Figure 1). A filter wheel, holding two polarisation filters and a calibration hot load, has replaced the original hot load in front of the cryostat window. No other modifications of the optics were required. In order to avoid mechanical or optically induced microphonics, the reflection-type half-wave plate is rotated on an air bearing.

Photometric mode

As LABOCA is a sparsely sampled array, a given source is seen by a single bolometer for only ~ 1/16th of the observing time for a Nyquist sampled map. After the wobbler became available, a more efficient photometric mode was offered to the community as a means of determining flux densities of compact sources without spatial information, but with high sensitivity. This was done by using the APEX wobbler to chop symmetrically between the target and nearby off positions in a similar way as is done for heterodyne observations. For the LABOCA implementation, the key was to use a sensitive bolometer on the optical axis[a] to stare at the target source, while the other elements produced redundancy in estimating the sky emission. This was a good way of integrating deeper in compact regions but this mode still required an exquisitely stable atmosphere and was prone to systematic errors such as spillover of ground radiation as a result of imperfections in the secondary mirror surface. While this photometric mode was quite popular from 2010 to 2013, it lost its relevance for compact point sources as ALMA could reach better sensitivity significantly faster than LABOCA. This mode was therefore decommissioned in August 2016.

Working with cryogenics at 5100 m

The safe handling of cryogenic liquids at 5100 m was one of the challenges in the operation of LABOCA. Thanks to strict procedures, this went fine apart from a small mishap when nitrogen was accidentally put into the helium tank. This required quick action to melt the nitrogen ice with a copper rod in order to avoid over-pressurising the helium tank. But even in regular operation, doing a daily refill of helium at 5100 m is quite a strain on operations. Everyone at APEX will remember the heroic "LABOCA rescue missions" involving a 130-km ride to the high site in the middle of a freezing night to top up liquid helium on the (thankfully rare) occasions when LABOCA unexpectedly ran out of coolant. All new APEX instruments after LABOCA have been designed to run with closed-cycle cryostats that can be fully remotely operated. One lesson learned from LABOCA was to mount the cryostat inside the moving Cassegrain cabin at an angle close to 45 degrees so that it is close to vertical during the observations. This is particularly important during the condensation phase of the recycling process. During the two hours of LABOCA recycling, we therefore restrict the elevation range of the observations with any other instrument between elevations of 30 and 60 degrees. Although this puts quite some constraints on the observing schedule, the APEX science operations staff have been able to successfully integrate these recycling restrictions into the observing plans. This applies to all closed-cycle cryostats based on pulse-tubes operating in the Cassegrain cabin.

Science highlights

The range of science targets observed during the 13 years of LABOCA operations is very wide. In the Solar System many asteroids were observed, including a time-coordinated campaign with Herschel and Planck to determine their variability and suitability as calibrators. Within our Galaxy, LABOCA observed debris discs, envelopes around stars, massive stars and even the entire Galactic plane observable from Chajnantor under the APEX Telescope Large Area Survey of the GALaxy (ATLASGAL). In extragalactic astronomy, LABOCA contributed to the study of dust in nearby galaxies, and galaxy clusters using the Sunyaev Zel'dovich effect. At high redshift, LABOCA made optimal use of the aforementioned fact that the flux of an object remains roughly identical from z = 0.7 to 10 to study radio galaxies, dusty star-forming galaxies and protoclusters. As it is impossible to cover all topics, we here present only a few selected highlights which illustrate the high synergy with other observatories, mainly ALMA but also Herschel and the VLT.

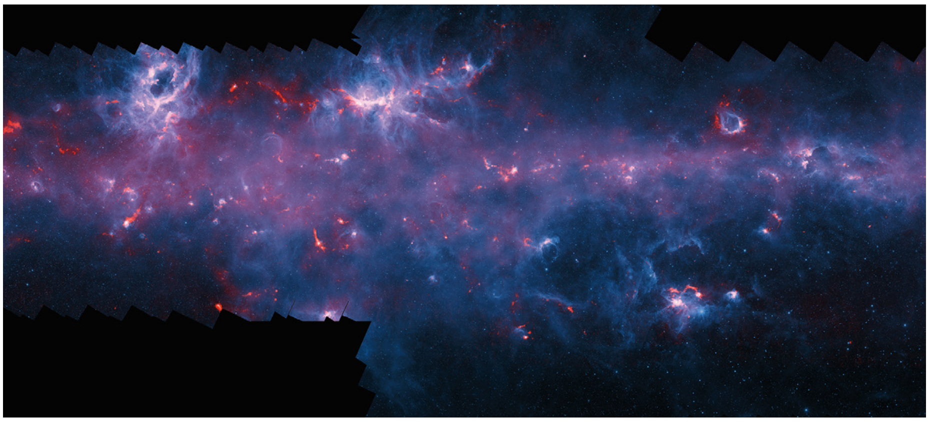

Figure 5. A subsection of the 870-μm ATLASGAL data shows up in red, while the background blue image is from the Spitzer Space Telescope as part of the 3.6-μm Galactic Legacy Infrared Mid-Plane Survey Extraordinaire. The fainter extended red structures come from complementary observations made by the Planck satellite.

Star-forming filament in Taurus

Characterising the origin of stars inside filaments is recognised as one of the major open questions in the field of star formation. The cosmic dust grains in these filaments are so cold that observations at submillimetre wavelengths by the LABOCA camera at APEX are needed to detect their faint glow. In order to better understand this process, Hacar et al. (2013) used LABOCA to study the Barnard 211/213 region in Taurus, a prototypical star-forming filament for this type of study.

The iconic LABOCA map of the Barnard 211/213 region (Figure 3) exemplifies the complex interplay between cloud structure and the origin of stars. In this image, two newborn stars are recognisable as bright spots highlighted by the glowing warm dust around them. A series of additional starless condensations indicate the presence of dense cores on the verge of collapsing to form yet more stars. Connecting these cores and stars, LABOCA also detects the fainter dust emission of the cloud extending over more than 10 light-years. For the first time, the enhanced sensitivity of this LABOCA image, comparable in quality to similar space observations obtained by Herschel, revealed the internal structure of this paradigmatic filament. In a pioneering discovery, the combination of this LABOCA image with additional molecular line observations demonstrated the existence of dozens of small-scale sub-filaments, known as fibres, bundled together in space and forming an elongated structure on large scales.

Cold dust present in star-forming regions

LABOCA is well suited to measuring the amount of cold dust present in star-forming regions, with a spatial resolution which corresponds well to the typical sizes of nearby protostellar envelopes (~ 10 000 au). The Orion A and B giant molecular clouds have been studied most extensively, with a total coverage of 5.2 square degrees. This includes the Orion Nebula region with the famous "Integral Shaped Filament", the L1641 cloud to its south, and NGC2023, NGC2024, Ori B9, NGC2068, NGC2071 and L1622 in the Orion B cloud. Data reduction was optimised to recover as much of the extended emission as possible (it tends to be filtered out by sky-noise removal), while maintaining excellent sensitivity in the compact sources. Figure 4 shows an overview of the entire survey area in the middle, and two close-ups of NGC 2071/2068 and the Orion A giant molecular cloud.

Together with more targeted, smaller-field SABOCA mapping, the LABOCA Orion survey data provided submillimetre photometry for more than 300 protostar candidates, identified from Spitzer thermal infrared imaging. These data were essential in determining the reservoir of gas that is still available in the protostars' cold envelopes for accretion onto their central star and disc. Together with a Herschel survey using the Photodetector Array Camera and Spectrometer (PACS) at 70, 100, and 16 μm — the Herschel Orion Protostar Survey (HOPS) — spectral energy distributions were obtained over the full infrared to submillimetre regime (Furlan et al., 2016); this included a sample of protostars that were actually too cold to be detected by Spitzer, which were found serendipitously in the Herschel maps (Stutz et al., 2013) and included in the LABOCA wide-field maps. This

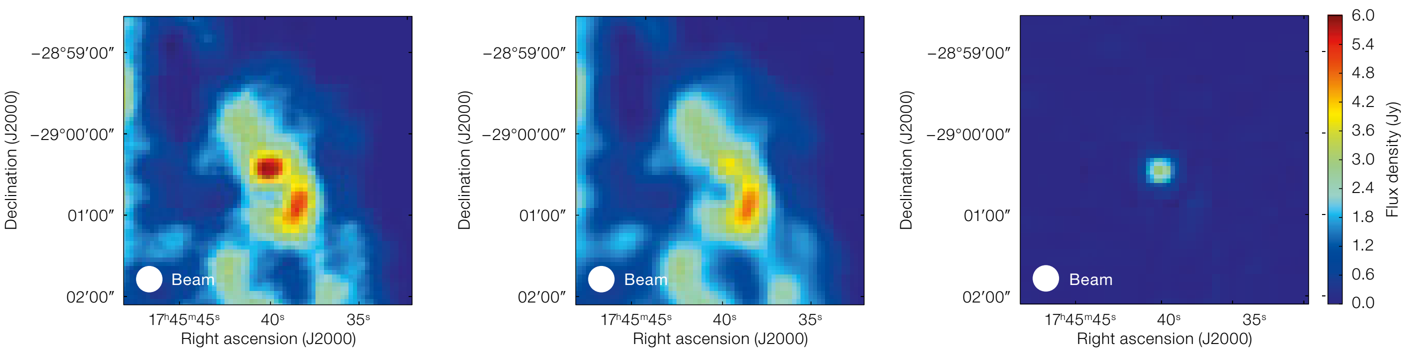

Figure 6. Data reduction process for the LABOCA campaigns. All maps show the innermost 3.5 × 3.5 arcminutes. Left: a single measurement map of the Galactic centre from a typical observation. Centre: model of the extended submillimetre emission from the Galactic centre: co-added maps with subtracted point source at the position of SgrA*. Right: remaining map after subtracting the model from the data. The point-like source represents the submillimetre emission from SgrA* itself (Subroweit et al., 2017).

arguably makes HOPS protostars the largest and best characterised protostar sample in a single star-forming region (Fischer et al., 2017).

ATLASGAL

The ATLASGAL survey (Schuller et al., 2009) is the single most successful APEX large programme with nearly 160 associated science papers[1] receiving over 4600 citations. The legacy of this survey will continue, thanks to the reduced data products publicly available through ESO Phase 3 data[2], catalogue release[3] and the ATLASGAL Database Server[4]. The ATLASGAL maps cover an area of sky 140 degrees long and 3 degrees wide. ATLASGAL complements observations from ESA's Planck and Herschel satellites. The combination of the Planck and APEX data allowed astronomers to add information on the diffuse emission across the survey area and to estimate the fraction of dense gas in the inner Galaxy (Csengeri et al., 2016). The ATLASGAL data were also used to create a complete census of cold and massive clouds where new generations of stars are forming.

The ATLASGAL project has led to a sustained flow of follow-up projects using ALMA and many other telescopes. The catalogue of compact clumps extracted from the ATLASGAL images was recognised as the best, least biased, and most representative database from which to extract a suitable sample for follow-up spectroscopic observations in molecular lines to characterise the physical and chemical conditions of dense molecular clumps associated with high-mass star formation over a wide range of evolutionary states (Foster et al., 2011). This catalogue was also ideal for drawing up a sample of massive dense clumps for high-spatial-resolution (down to 0.06 pc) follow-up observations with ALMA (Csengeri et al., 2017). The Search for high-mass Protostars with ALMA Revealed up to Kiloparsec Scales project (SPARKS) is now delivering its first results. Finally, by complementing the ATLASGAL data with spectroscopic observations to derive distances and with existing infrared surveys, Urquhart et al. (2018) could draw a detailed picture of the changes in physical properties (temperature, luminosity, onset of star formation) during the early evolution of high-mass protostars and proto-clusters. These results are based on a complete sample of ~ 8000 dense clumps, the largest sample of submillimetre dense clumps with reliable distance estimates to date.

Time-domain science

One of the strengths of APEX is its considerable scheduling flexibility, which makes it optimal for monitoring campaigns. LABOCA has observed several

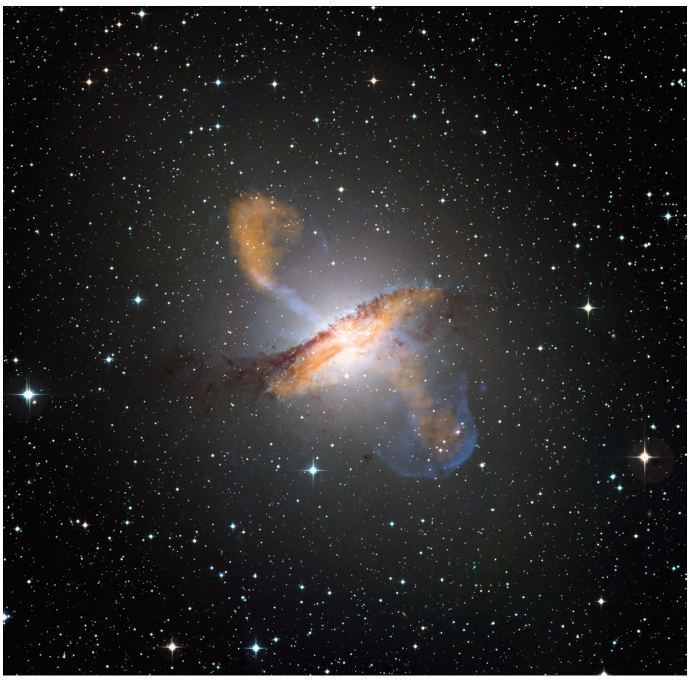

Figure 7. This image shows a colour composite image of the radio galaxy NGC 5128, aka Centaurus A, revealing the lobes and jets emanating from the active galaxy's central black hole. This is a composite of images obtained with three instruments, operating at 870 μm (LABOCA: orange), in X-rays (Chandra X-ray Observatory: blue) and in visible light (Wide Field Imager [WFI] on the MPG/ESO 2.2-m telescope at La Silla); it shows the stars and the galaxy's characteristic dust lane in close to "true colour".

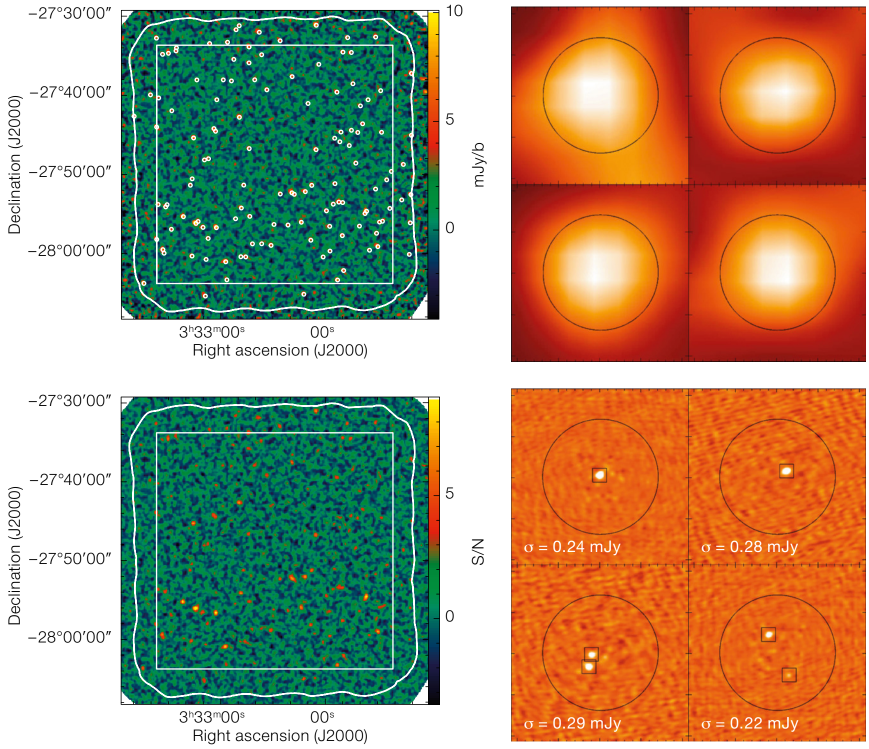

Figure 8. The image on the left shows the LABOCA map of the ECDFS with 122 sources detected (Weiß et al., 2009). This map illustrates the source-finding capabilities of LABOCA, which allowed deeper and higher-resolution ALMA follow-up observations (see the 44 x 44-arcsecond images on the right, from Hodge et al., 2013 and Karim et al., 2013).

classes of objects that show significant variability in their submillimetre continuum, such as gamma-ray bursts (for example, de Ugarte Postigo et al., 2012), blazars (Fuhrmann et al., 2014) and supermassive black holes.

The Galactic centre was monitored over eight epochs between 2008 and 2014 in a coordinated campaign with the NAOS–CONICA instrument (NACO) on ESO's VLT. The data show observational evidence that, together with theoretical modelling, supports the idea that the SgrA* synchrotron flare spectra are optically thin in the near-infrared and peak in the 350-GHz range (Eckart et al., 2012 and references therein; see Figure 6). Subroweit et al. (2017) performed a statistical analysis of the variable 100- and 345-GHz flux densities of Sgr A* and find that both flare flux density distributions are well described by power laws with an index around 4. Using a plasmon model to explain the flares one can constrain the important model parameters: the initial synchrotron turnover frequency of the flare source components and their expansion velocity is mostly above 100 GHz and below a velocity value of 0.01 *c* (Eckart et al., 2012).

Time-domain science carried out by Dharmawardena et al. (2020) using LABOCA archival data of Betelgeuse, in combination with more recent SCUBA-2 data, showed that its submillimetre luminosity has dimmed by about 20% during its optical minimum.

Nearby active galaxies

In the 1970s, the first observations of the (sub)millimetre continuum emission in nearby galaxies showed the importance of this wavelength regime for studying optically thin emission from cold dust in galaxies and the variability of synchrotron emission in active galactic nuclei (for example, Hildebrand et al., 1977; Elias et al., 1978). It took about another decade of technology development until the first (sub)millimetre maps of nearby starburst galaxies became available which showed the distribution of gas and its relation to the nuclear activity in infrared-bright systems such as M82 and NGC253 (Krugel et al., 1990). LABOCA, with its large field of view and high sensitivity submillimetre maps, was finally sensitive enough to also study the cold dust in the discs of nearby galaxies, which are often ~ 20–30 times fainter than active nuclear regions but carry comparable amounts of dust.

Figure 7 shows one of the first high-fidelity LABOCA images of Centaurus A (Weiß et al., 2008) combined with optical data taken with the MPG/ESO 2.2-m telescope and X-ray data observed with Chandra (Kraft et al., 2000). It reveals not only emission from cold dust associated with the prominent dust absorption lanes, but also the synchrotron emission from the radio jets emerging from the accreting supermassive black hole at the centre of Centaurus A. The LABOCA observations show that material in the jet is travelling at about half the speed of light. This image has become a textbook example in journals and the media to illustrate high-energy phenomena in galaxies.

LABOCA ECDFS Submillimetre Survey

The flagship extragalactic project during the first years of LABOCA was a deep survey of the Extended Chandra Deep Field South (ECDFS), producing 34 papers which have received more than 3000 citations. Such a survey was foreseen in the science justification of APEX itself. An investment of 320 hours of the best weather conditions (precipitable water vapour, PWV < 1 mm) effectively monopolised this range in Local Sidereal Time for the first two years of LABOCA operations, but the yield was enormous. The LABOCA ECDFS Submillimetre Survey (LESS; Weiß et al., 2009; Smail, Walter & LESS Consortium, 2009) was the largest uniform extragalactic survey of its time, covering a region the size of the full Moon. The final map, shown in Figure 8, is available from the ESO Phase 3 interface[5]. The observing mode and data reduction procedures developed for LESS have become the standard for all deep extragalactic mapping projects with LABOCA. On the science side, the LESS map set a new standard — the follow-up of the 120 sources in the map was the foundation for one of the highest-impact projects when ALMA entered operations in

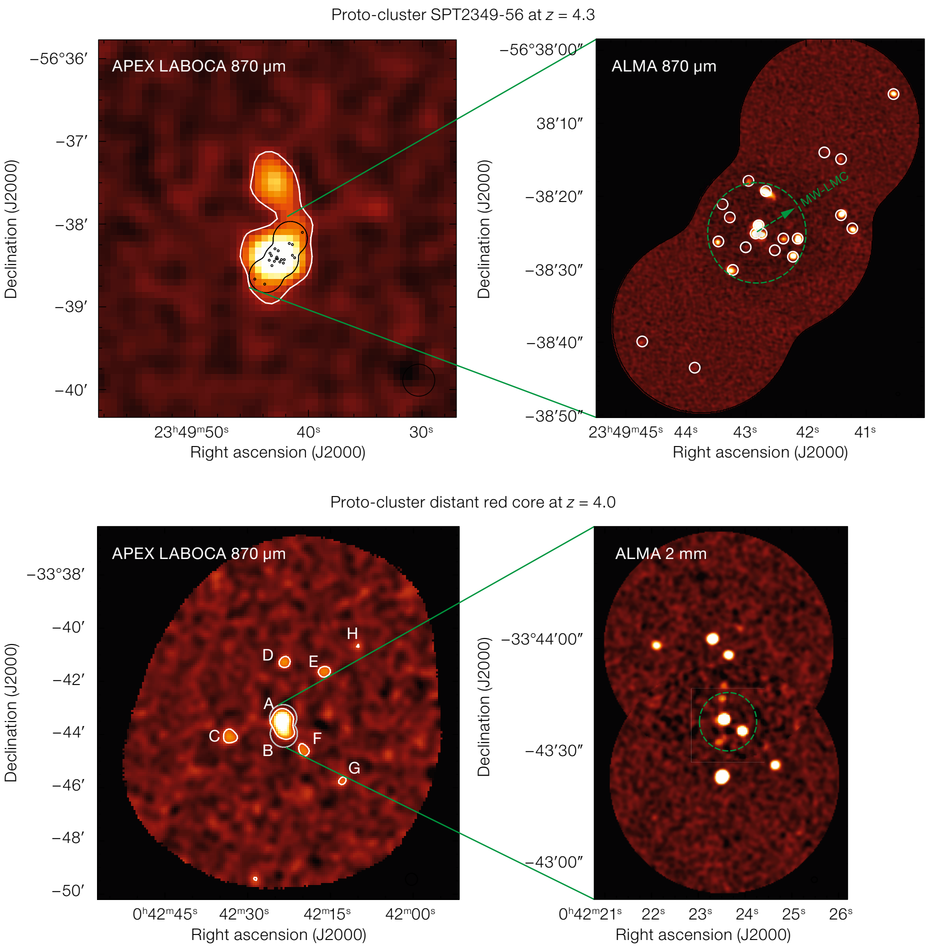

Figure 9. Top: LABOCA 870-µm image of the SPT 2349-56 system at redshift z = 4.304 overlaid with the ALMA coverage towards the southern LABOCA source (black contour; the white contour is the 4σ LABOCA signal-to-noise ratio; Miller et al., 2018). At top right is the ALMA 3 pointing mosaic of the high-spatial-resolution 870-µm continuum emission underlying the [CII] emission line that identifies 21 individual galaxies as members of this protocluster. The core of the protocluster contains 15 (Ultra) Luminous InfraRed Galaxies, (U)LIRGs, with a projected separation equal to the MW–LMC distance only (dotted green circle). Additional ALMA data show that the northern LABOCA source is also part of this system (Hill et al., 2020). Bottom: same presentation for the distant red core at z = 4.002 with the ALMA footprint shown as grey contour. The ALMA 2-mm continuum shows that the distant red core consists of 10 (U)LIRGs at the same redshift. In addition to the protocluster core the LABOCA image reveals an overdensity of submillimetre galaxies (SMGs) in the vicinity of the distant red core that may also be part of this structure (Oteo et al. 2018; Lewis et al. 2018; Ivison et al., 2020).

2012 (Swinbank et al., 2012). Imaging the LESS sources at much higher spatial resolution was one of the first projects undertaken when ALMA entered science operations (Hodge et al., 2013). The redshift determination and study of the properties of the 120 LESS sources are still ongoing using the VLT, ALMA (Danielson et al., 2017; Wardlow et al., 2018) and soon using the JWST. It took SCUBA-2 at the JCMT over a decade to cover an area 10 times wider than LESS to comparable depth, while ALMA's largest areas are < 10% those of LESS.

Gravitationally lensed dusty star-forming galaxies

One of the most unexpected discoveries made with LABOCA happened in May 2009, while observing a lensed z = 3 galaxy called the "Cosmic Eye". While the source remained undetected, the observation showed a bright 100-mJy source about 1 arcminute away. The observer (one of the authors of this paper) first suspected this was due to an error in the pointing model because of a recent intervention. However, further investigation revealed that it coincided with another triple-lensed system. A quick follow-up with the Green Bank Telescope determined a redshift of z = 2.3 for this source, the first time this was done using a blind CO search. This system, magnified ~ 32 times, was dubbed the "Cosmic Eyelash" because of its shape and proximity to the Cosmic Eye (Swinbank et al., 2010). It provided, thanks to a string of DDT proposals, a first insight into the kinematics, chemistry and interstellar medium properties of a high-redshift star-forming galaxy at the spatial resolution and signal-to-noise which would take another 5+ years for ALMA to match. At the time of discovery, the Cosmic Eyelash was the only high-redshift source sufficiently bright to use to commission instruments aboard Herschel.

This chance discovery was possible thanks to LABOCA's wide field of view and it became the prototype of the population of lensed submillimetre galaxies. These distant objects can be studied in unprecedented detail thanks to the gravitational magnification that boosts the total intensity and allows their intrinsic structure to be resolved.

While the Cosmic Eyelash was a chance discovery, LABOCA would soon start playing a crucial role in a systematic search and characterisation of this population of lensed dusty star-forming galaxies selected using wide-field surveys with the Herschel Space Observatory and the South Pole Telescope (SPT). The high sensitivity and sharper spatial resolution of LABOCA were critical to providing complementary 870-µm photometry and separating them into point-like strongly lensed high-redshift galaxies and protoclusters which are typically spatially extended with LABOCA. LABOCA enabled the discovery of the most distant objects in both of these categories (Strandet et al., 2017; Miller et al., 2018; and Oteo et al., 2018).

LABOCA in numbers

A total of 596 LABOCA proposals have been approved for scheduling by the proposal committees in Sweden, Chile, MPIfR and ESO, of which 327 are associated with data[b]. Based upon one or more

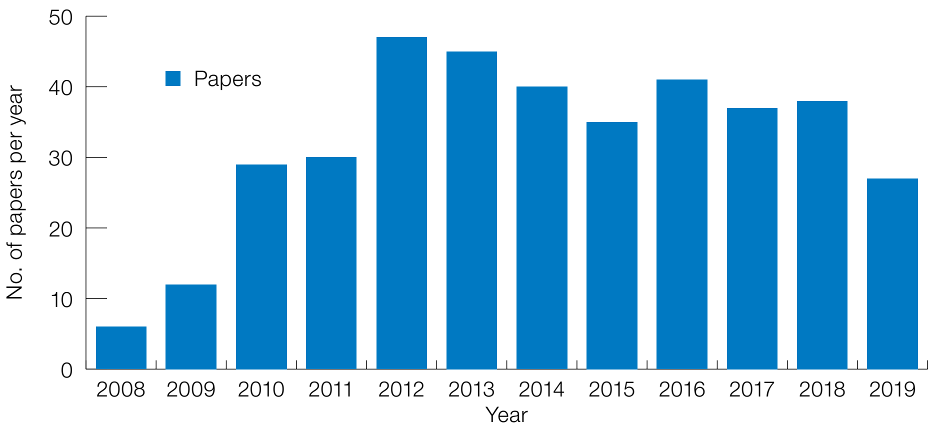

Figure 10. The number of papers published per year between 2008 and 2019 in refereed journals based on data obtained with LABOCA.

of these data sets, 387 papers have been published between 2008 and 2019, which corresponds to an average of 32 papers per year.

Over the years, LABOCA has been observing for 9300 hours (193 000 scans), out of which 7900 hours were scans of a scientific nature (on, raster, and on-the-fly mapping [otf]) and 1400 hours were of calibration-type nature (point, go, focus, cal, and skydip). About 70% of the scans were observed with pwv < 1 mm. It should be pointed out that the observing time includes instrument setup and telescope movement time, so the true on source time is lower than this number.

LABOCA has (so far) been cooled down approximately 47 times at APEX. In total the cryostat has been kept cold for a total of 1893 days, i.e., more than 5 years. In order to achieve this, the contents of 82 250-l liquid helium dewars have been consumed (an estimated total of 20 500 l). Given that 387 LABOCA papers have been published using a total of 9300 hours, each paper corresponded to a consumption of 53 l of liquid helium, or 2.2 l per hour. This number will decrease with time as more papers continue to be published after LABOCA is decommissioned.

Beyond LABOCA

LABOCA turned out to be one of the most robust APEX instruments and it has outlived its originally expected lifetime (for example, the ABBA computer is still working after 15 years!). Its space in the Cassegrain cabin will now be taken by the CarbON CII line in post-rEionization and ReionizaTiOn epoch project (CONCERTO), which will add a spectral domain to wide-field bolometer imaging (The CONCERTO collaboration et al., 2020). However, as a pioneering wide-field submillimetre camera in the southern hemisphere, LABOCA leaves a data archive with a legacy value that will certainly lead to a further growth in the number of LABOCA papers in the future.

Acknowledgements

We acknowledge the use of ESO press releases and images. We also thank the people who have contributed to building and operating LABOCA over the last two decades. In particular, we want to thank Gundula Lundershausen, Walter Esch, Hans-Peter Gemünd, Eugene E. Haller and Jeff Beeman for their critical contributions to the development and construction of LABOCA. Finally, we thank the LABOCA users who conceived such a diverse set of science observations.

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Links

[1] ESO Telescope Bibliography: http://telbib.eso.org/
[2] ATLASGAL ESO Phase 3 data query form: http://archive.eso.org/wdb/wdb/adp/phase3_main/form?phase3_collection=ATLASGAL&release_tag=1
[3] ATLASGAL catalogue release: https://www.eso.org/qi/catalog/show/67
[4] ATLASGAL database server: https://atlasgal.mpifr-bonn.mpg.de/cgi-bin/ATLASGAL_DATABASE.cgi
[5] LESS ESO Phase 3 data query form: http://archive.eso.org/wdb/wdb/adp/phase3_main/form?phase3_collection=LESS&release_tag=1

Notes

[a] Ideally, one would use pairs or triples of bolometers to spend even more time on source, but moving away from the optical axis introduced too many uncertainties.
[b] The reasons for the discrepancy are that some projects were not (yet) observed, and in some cases the data are associated with another project code (i.e., when a proposal is resubmitted to different periods and/or when a proposal is submitted to more than one partner).

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ALMA Data Quality Assurance and the Products it Delivers — The Contribution of the European ARC

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From its inception, the Atacama Large Millimeter/submillimeter Array (ALMA) was intended to be accessible to all astronomers, including those who are more used to carrying out their research at other wavelengths. Since the beginning of science observations in September 2011, ALMA has therefore applied a comprehensive Quality Assurance (QA) process to the observed data before delivering them to the principal investigators (PIs). This huge investment, unique for a ground-based (non-survey) observatory of this calibre, results in fully calibrated datasets as well as high-quality images that allow the PIs to assess the quality of their data upon delivery and that provide an advanced starting point for the scientific analysis. In this article we provide a summary of the purpose and status of ALMA QA, a brief description of the QA process and the resulting ALMA data products, and a discussion of how the ALMA user profits from them.

ALMA observations and data processing

The considerable effort going into ALMA QA is provided by staff at all four main locations of the ALMA project: the Joint ALMA Observatory (JAO) in Chile, and the three ALMA Regional Centres (ARCs) in East Asia, North America and Europe[a]. In Europe, the work is done by the ARC staff at ESO in Garching as well as staff in the European ARC network. For a description of the European ARC network see Hatziminaoglou et al. (2015).

In their observing programmes, ALMA PIs do not propose for observing time but for a particular sensitivity at a range of angular scales to achieve their science goal (the required strategy can also include time constraints). The observations and their scheduling are based on Scheduling Blocks (SBs) — the observing units defined within each science goal. A SB is a plan for a complete set of calibration and science target observing scans (see Figure 1). Several different SBs may be needed to define the observations necessary to achieve one science goal: for example, observations from different array configurations. The total duration of a SB execution can be up to two hours. If longer exposures are required on the target, the same SB is executed several times. The details of the SB setup and the number of required SB executions (the so-called Execution Blocks, EBs) are estimated based on the ALMA Sensitivity Calculator and the parameters provided by the PI in the proposal using the ALMA Observing Tool (OT).

Level 0 quality assurance (QA0) takes place at the telescope shortly after the completion of the execution of a SB. It aims to catch obvious problems with the observation at an early stage and ensure that the data collected during this particular execution are useful to achieving the science goal. A number of diagnostics are created in order to permit a basic check of the correct setup of the included antennas and their receivers and to quantify the overall stability of the atmosphere; in addition, QA0 verifies that the flux calibrator used in the observation has a recent flux measurement.

If the execution has achieved a significant fraction of the intended science observation, it can move on to the following QA stage and is declared "QA0 Pass". It is stored in the ALMA Science Archive and is replicated from the JAO to archive copies at the three ARCs. A SemiPass or Fail state indicates a partially useful execution or an execution that cannot be calibrated at all, respectively, and the execution is repeated. The contribution of each EB is measured as a so-called "execution fraction", factoring in the observing conditions and number of available antennas. The execution fraction can be larger than unity if the conditions are better than expected. Once the sum of the EB execution fractions is equal to the planned number of EBs, the SB is considered fully observed.

Level 2 quality assurance (QA2) takes place once an SB is fully observed. Note that there is also a level 1 QA which concerns the longer-term monitoring of observatory parameters, but this is not discussed in this article. The full set of executions of an SB is called a Member Observation Unit Set (MOUS). The MOUS

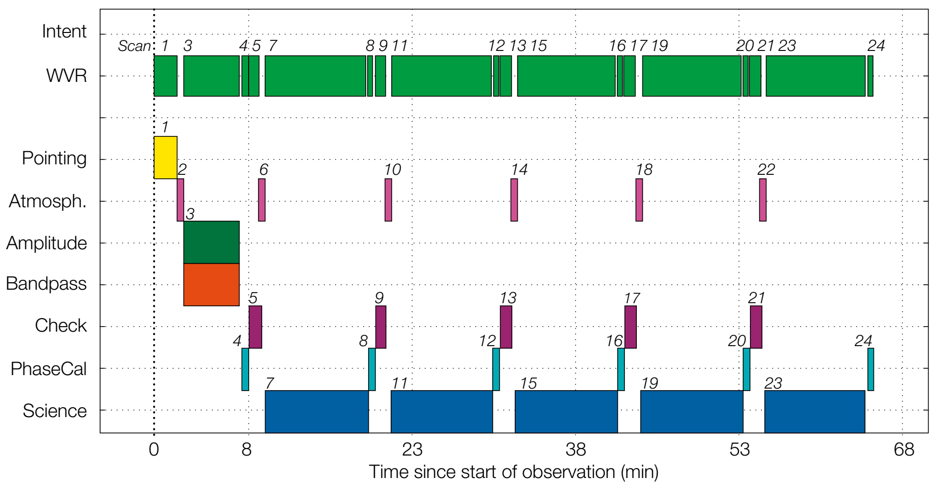

Figure 1. Typical structure of an ALMA Scheduling Block (SB) describing the interleaved observation of a single science target (dark blue), a phase calibrator (light blue), a check source (dark purple) to assess the quality of the phase transfer, and other calibrators. Also shown are the calibrator scans during which water vapour radiometer data are taken (light green) and the receiver response and the atmospheric opacity along the line of sight are measured (light purple).

is the smallest data entity that is delivered to the PI. Thus, QA2 operates on MOUSs.

While QA0 takes place at the observatory, QA2 is decentralised. Up to the end of ALMA Observing Cycle 1 (September 2014), essentially all QA2 processing took place at the three ARCs. After that, the capabilities of the JAO were extended, and QA2 processing was gradually moved there.

QA2 processing is computing intensive. In the typical case of an interferometric dataset[b], it consists of three steps: the a priori calibration, the calibration of flux, bandpass, and phase, and the imaging.
– The a priori calibration applies initial phase and intensity corrections based on the water vapour column density, the receiver response and the atmospheric opacity measured during the observations, applies small positional updates of the antennas, and runs an initial flagging of bad data.
– The flux, bandpass, and phase calibration makes use of dedicated observations of calibrator targets that are integrated into the SB, interleaved with the observations of the science target(s) (see Figure 1). The flux calibration bootstraps the flux scale to an absolute scale by comparing to recent observations of a known quasar calibrated against a Solar System object with well-known emission. The bandpass calibration corrects for the spectral response of the ALMA receivers by observing a bright quasar with a featureless, non-thermal spectrum. Finally, the phase calibration derives a correction for the atmospheric phase fluctuations from the observation of another bright quasar at a small angular distance from the target. All these steps may require iteration if bad data is found during the processing that needs to be flagged. For full-polarisation observations, another calibration step is needed which applies the information gained from the observations of a polarisation calibrator over a sufficiently large parallactic angle range.
– Finally, imaging is carried out on the calibrated data for all spectral windows and for as many of the science targets as possible with the available computing resources. While the calibration of a MOUS (i.e., all the executions of an SB) typically takes between 1 and 24 hours, the imaging of (spectrally and/or spatially) high-resolution observations can take between half a day and several weeks of computing time. For line observations, the imaging process also includes the determination and subtraction of the continuum emission before imaging the line cubes.

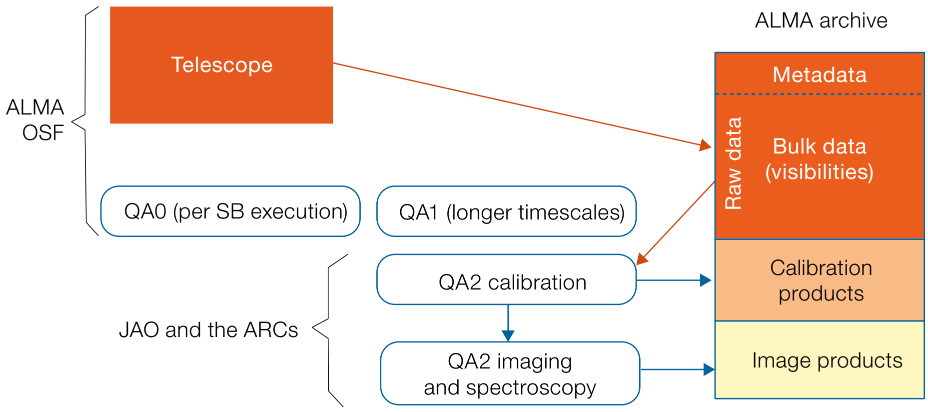

Figure 2. Simplified ALMA data flow. While the raw data go straight to the Archive after QA0, the calibration and science products are generated during QA2, which takes place at the JAO and the ARCs. Note that the calibration products do not include the calibrated visibilities in order to save Archive storage space.

The QA2 processing is followed by an assessment of whether the sensitivity in the representative spectral range and the achieved angular resolution match the PI's requirements as recorded in the proposal. If they do, the dataset is declared "QA2 Pass" and the calibration and image products are ingested into the Archive. The successful ingestion is followed by an email notification to the PI to advertise the availability of their data. This is called the delivery and starts the proprietary time of one year. Access to proprietary raw data is also possible upon request before the official delivery, but this request immediately starts the clock for the proprietary time and comes without any user support from the ARCs with the calibration.

If a dataset does not pass QA2 immediately (< 10% of the cases), re-observation of the SB followed by new QA2 processing is attempted until the project times out (for details see Remijan et al., 2019). This is another reason why QA speed is of the essence.

In order to save storage space, calibrated visibilities and single-dish data are not stored in the Archive and are not part of the data delivery. Instead, all products necessary for the calibration are provided. The user has to restore the calibrated data by running a script contained in the delivery package on the raw data. Since October 2019, the calibrated data can also be requested for download via a dedicated service offered in Europe[1]. Before the end of the proprietary time, the service is of course only available to PIs and data delegates.

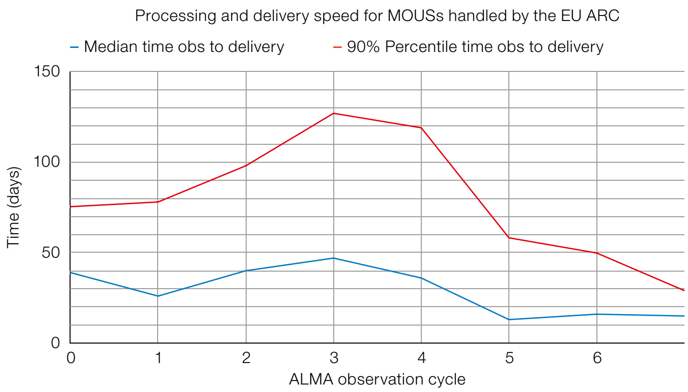

Figure 3. The processing and delivery performance of the QA work at the EU ARC. After some overload and technical problems in Cycles 3 and 4, 90% of the deliveries now take place within one month after observation.

In summary, QA2 processing of the full set of executions of an SB is a complete, high-quality, science-ready calibration of the data followed by detailed imaging with the aim of providing the PI (and later archival researchers) with a set of images that make it possible to inspect the degree to which the science goals were achieved.

A Level 3 quality assurance (QA3) process has been put in place to handle any errors that are discovered after the official data delivery. If the problem is discovered by a user, they may file an ALMA helpdesk ticket. If confirmed, a detailed investigation is started. The outcome ranges from the addition of a note to the QA2 report to a correction of the data products, followed by a re-ingestion into the Archive, or if necessary and possible, even a re-observation of the SB. In ten years of ALMA observations, QA3 cases that affected large portions of ALMA data have happened only a few times. In all cases, the observatory strove to keep the users informed about the implications of the problem for their data and about the progress of the correction. Obviously, every such campaign implies a high additional load on the QA staff and the computing facilities.

From semi-manual to pipeline processing

Full automation of QA2 processing was always planned but cannot be achieved without a period of semi-manual processing until the data are fully characterised. In ALMA observing Cycle 1 (September 2014), all QA2 processing was carried out exclusively semi-manually by analysts using the Common Astronomy Software Applications package (CASA; McMullin et al., 2007; Petry, 2012; Emonts et al., 2019) and the Calibration Script Generator, a tool that evaluates ALMA raw data and generates a draft calibration script (see Petry et al., 2014). Based on the experience gathered with this prototype pipeline, a fully automated pipeline was developed and gradually deployed cycle by cycle for more and more of the different ALMA observing modes. In particular, the heuristics for automated flagging and calibration were deployed first. The capability to automatically image the data followed in the middle of Cycle 4.

Like the semi-manual analysis, the ALMA pipeline (ALMA pipeline Team, 2019) is based on the CASA package. It is distributed together with CASA and thus also published to ALMA users. For QA2, it runs at the JAO and the ARCs, controlled by additional infrastructure software. For each run, the pipeline creates a set of diagnostic plots and tables (wrapped in a system of html pages), called the weblog. This weblog is then reviewed manually in order to judge whether the pipeline run was successful, and the observing parameters were met.

Today, the ALMA pipeline is capable of processing most ALMA data without much human intervention other than reviewing the weblog. Only about 10% of the datasets still require semi-manual processing by analysts. For projects supported by the European ARC, these analysts are based at the European ARC network including the ESO ARC department. Similar efforts are ongoing in the other ALMA regions, and of course at the JAO.

During the first observing cycles, the delays between data taking and data delivery were significant. Today, thanks to an enormous effort at the JAO and the three ARCs, a complete redesign of the data flow system, and the increased usability of the ALMA pipeline, QA2 processing has been accelerated to the point where 90% of the deliveries take place within one month after the observation (the median is 2 weeks).

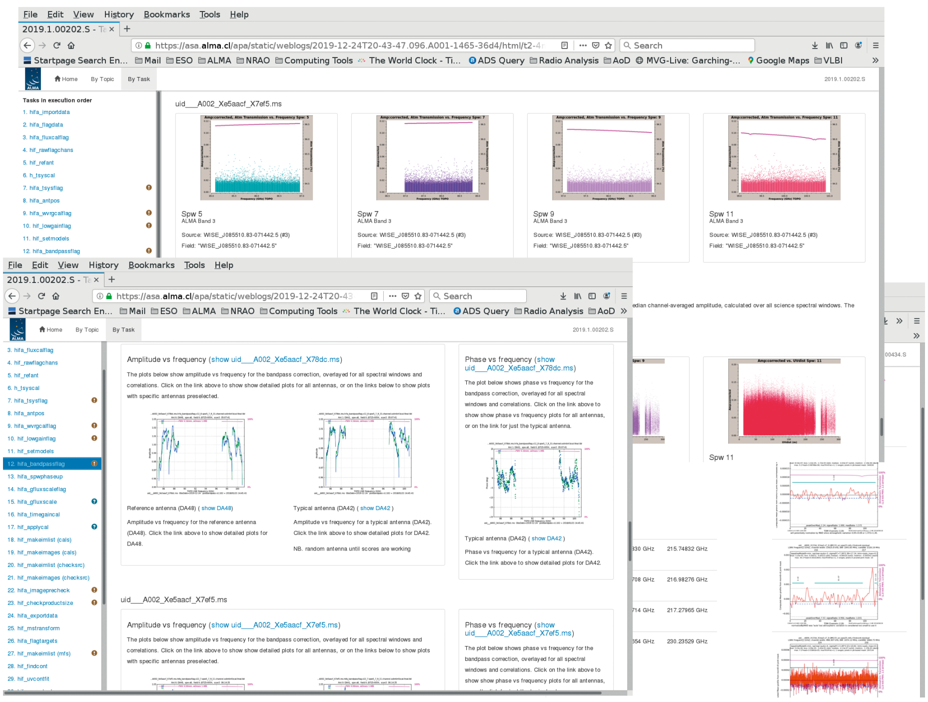

Figure 4. A sample of ALMA pipeline weblog pages showing different diagnostic plots.

Why is QA2 necessary and what does it provide to the user?

ALMA is a large, complex project that needs to perform detailed bookkeeping and monitoring to make sure that the observatory performs reliably and to specification. The QA effort is part of this process, providing a vital link in the chain from the proposal of an observation to the publication of its scientific results. Experience has shown that subtle problems are often only noticed when trying to extract scientific information from the data. Furthermore, the only precise method of determining the achieved sensitivity is to fully calibrate the data and create an image of the spectral range that is of interest to the PI. Finally, to optimise the extraction of scientific results from its archive, ALMA would like to provide

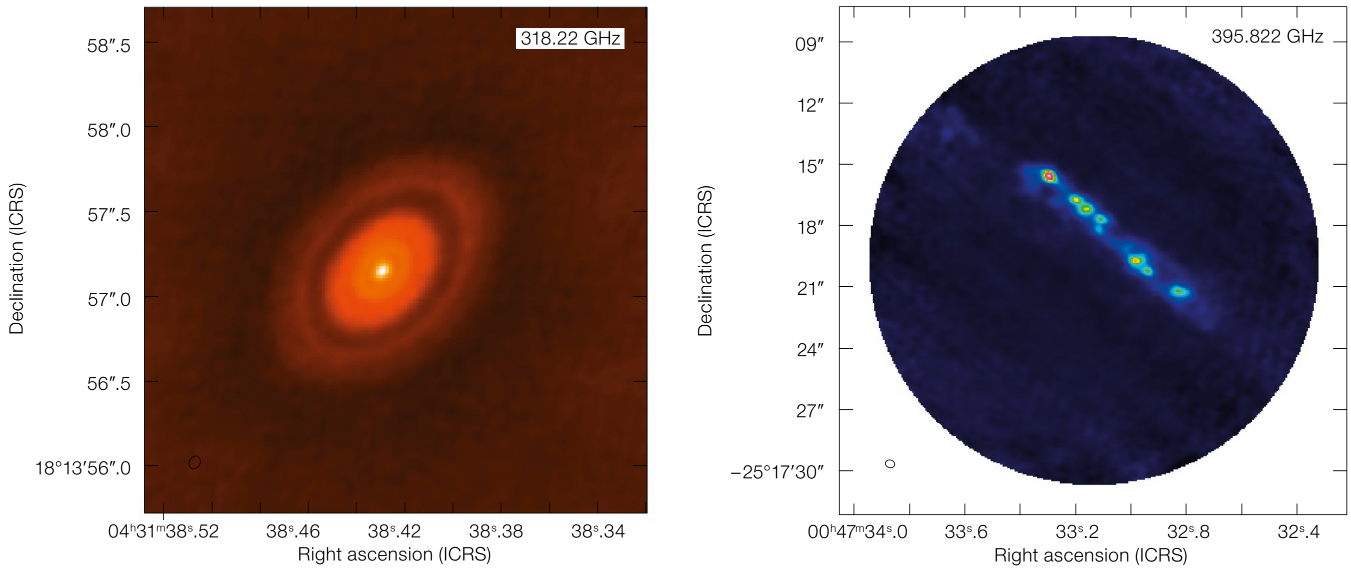

Figure 5. Two examples of science target images created during ALMA QA2 and delivered to the corresponding PIs.

valid data products to facilitate archival research. The QA2 process combines all three of these processes and presents ALMA users with two major advantages:
1. An advanced starting point for their own data analysis which helps PIs to publish sooner and better.
2. A valuable, comprehensive, and most of all, homogeneous set of high-quality data products for more efficient archival research.

As a result of the QA2 effort and in addition to the raw data, PIs receive for each individual dataset (MOUS) a standard package with a wealth of important information:
- The science-grade calibration information. The user can take their raw data and calibrate it in a reproducible way by running the CASA script "scriptForPI.py" included in the package. Each data set is processed with a specific CASA version. The user is required to run the scriptForPI under that CASA version. Alternatively, European users can request the generation of the calibrated data from the European ARC via the helpdesk.
- A detailed summary of the QA stages in the form of QA0 and QA2 reports.
- All calibration and imaging diagnostic plots (for pipeline-processed data in the form of the weblog, see previous section). This permits the user to assess nearly all details of the data properties without having to touch the raw data or even starting CASA. The weblog is simply opened in a web browser (see Figure 4).
- The QA2 imaging products as FITS files (following FITS standard 3.0). This package contains aggregate bandwidth, continuum, and line-cube images depending on the science goal. Calibrator and check source images are also typically included. The completeness of the set is typically better for pipeline-processed datasets since the semi-manual imaging process is slower and needs to save time for quick delivery.

For a detailed description of the ALMA QA2 data products see Petry et al. (2018).

Are ALMA image products science-ready?

As described above, ALMA QA2 is a standardised and semi-automated process that is not meant to cover all of the specific scientific needs of the PIs. Feedback from users indicates that the delivered standard images and cubes are often close to optimal and can be used as a basis for scientific analysis. However, it should be clear to all ALMA users, PIs and archive researchers that the delivered images cannot, in general, be classified as science ready. The user may well have to go back to the calibrated data to optimise the parameters of continuum subtraction and/or imaging for their scientific goal, in order to obtain the image or cube for publication. Extensive help in assessing the standard products and improving on them is provided to all European users by the European ARC network and the helpdesk.

Although ALMA strives to provide high-quality and homogeneous informative imaging products for all datasets, the imaging products from the earlier Cycles 2 to 4 were produced semi-manually and are often only based on a fraction (at least 200 channels of most spectral windows) of the total spectral coverage. Additional Representative Images for Legacy (ARI-L) is an ongoing ALMA development project that aims at increasing the legacy value of the ALMA Science Archive by bringing the reduction level of ALMA data from Cycles 2 to 4 close to that of the more recent cycles, for which the imaging pipeline was used. These re-processed images and cubes are being included in the Archive as value-added products. Future Messenger articles will present the ARI-L project in more detail and also the ALMA Science Archive.

Other value-added data products come from the ALMA Large Programmes. The award of a Large Programme carries with

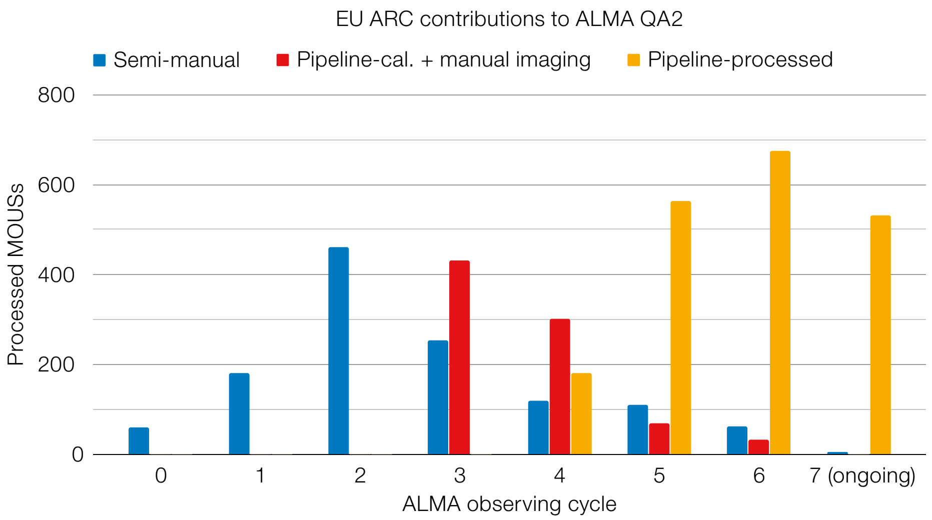

Figure 6. The MOUSs (individual ALMA datasets) QA2-processed and delivered by the European ARC and its nodes since the beginning of ALMA observations. The numbers are presented separately for the three main processing workflows: script-generator-assisted semi-manual processing (blue), pipeline calibration followed by manual imaging (red), and full pipeline processing (yellow). Note that pipeline processing also requires a human review of the results (called the weblog review).

it the responsibility to deliver back to ALMA a set of enhanced data products which supplement the standard ALMA products generated by the ALMA observatory during QA2.

Conclusions and forward look

Since the start of science observations, the ALMA project has put a huge effort into providing science-grade calibrated data and informative image cubes, a first for a large ground-based astronomical observatory. This effort is populating the ALMA Science Archive with homogeneous, high-quality data while making ALMA more accessible to all astronomers, regardless of their scientific background.

ALMA aspires to extend the user support even further: one of the project's longer-term goals is to produce higher level data products such as catalogues or images combining data at different angular resolutions from different SBs. Such products will further enable the use of the facility and its archive by non-expert users, increasing at the same time the scientific impact of the observatory. Making science-ready data products available will shift the focus of the users from the (hardware) limitations and the technicalities related to interferometric data reduction to the scientific exploitation of the data.

Acknowledgements

Over the past seven and a half ALMA observing cycles, the European ARC network has made major contributions to the ALMA QA effort. Scientists from ESO and the ARC network have worked more than 150 seven-day Astronomer-on-Duty shifts at the observatory and performed QA0 assessments as part of them. They have so far served as QA2 analysts for more than 1250 semi-manually calibrated, more than 830 manually imaged, and more than 1940 pipeline-processed datasets from European projects. Furthermore, they have contributed significantly to the development of the CASA package, the ALMA calibration and imaging script generators, and the ALMA pipeline.

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Links

[1] EU ARC webpage on requesting calibrated data in Europe: https://almascience.eso.org/local-news/requesting-calibrated-measurement-sets-in-europe

Notes

[a] Further details of the ALMA partners and the organisation of this large international project: http://almascience.org.
[b] There are other classes of observations that are not described here but which also undergo QA. These include single-dish SBs and special modes like solar or VLBI observations.

ALMA (ESO/NAOJ/NRAO), ESO/Exeter/Kraus et al.

ALMA and SPHERE work together to reveal the detailed structure of the warped disc around the triple star system GW Orionis. The disc is deformed by the movements of the three stars at its centre. The ALMA image (top) reveals a ringed structure, while the SPHERE observations reveal the shadow of the innermost ring on the rest of the disc.

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The VLT-FLAMES Tarantula Survey

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The VLT-FLAMES Tarantula Survey (VFTS) was an ESO Large Programme that has provided a rich, legacy dataset for studies of both resolved and integrated populations of massive stars. Initiated in 2008 (ESO Period 82), we used the Fibre Large Array Multi Element Spectrograph (FLAMES) to observe more than 800 massive stars in the dramatic 30 Doradus star-forming region in the Large Magellanic Cloud. At the start of the survey the importance of multiplicity among high-mass stars was becoming evident, so a key feature was multi-epoch spectroscopy to detect radial-velocity shifts arising from binary motion. Here we summarise some of the highlights from the survey and look ahead to the future of the field.

Massive stars have long captured our imagination. In stark contrast to the history and fate of the Sun, stars born with masses in excess of ~ 8 $M_\odot$ quickly fuse their hydrogen into helium and heavier elements on timescales of millions rather than billions of years. They evolve into classical Wolf-Rayet stars, luminous blue supergiants (for example, Rigel), and/or bloated, cool red supergiants (for example, Betelgeuse), before exploding catastrophically as supernovae. Massive stars are a key ingredient in models of galaxy evolution. They dominate the energetics and chemistry of their surroundings via their intense ultraviolet radiation fields and stellar winds. They also enrich the interstellar medium with nuclear-processed elements via their winds and ultimate explosions.

In the first decade of the millennium there was mounting evidence for the prevalence of binarity in massive stars but its exact impact was unclear, both for stellar evolution and in the wider context of massive-star formation in galaxies. It is now evident that most massive stars are formed in binary (and higher multiplicity) systems, with the great majority expected to undergo interactions that significantly influence the appearance and evolution of both stars through, for example, mass transfer, rejuvenation, merging, and spin-up (Sana et al., 2012). The detection of gravitational waves (GW) from merging stellar-mass black holes (Abbott et al., 2016) has brought the evolutionary history of massive stars into even sharper focus — if we are to understand the progenitors of these merger systems, we need a better understanding of the physical properties and evolution of massive stars.

To enable a big step forward in our understanding of massive stars, the VFTS was conceived to deliver the largest homogeneous, multi-epoch spectroscopic survey of O-type stars to date. A preceding ESO Large Programme, the VLT-FLAMES Survey of Massive Stars (Principal Investigator, PI: Smartt, ESO Programme ID 171.D-0237; Evans et al., 2008), investigated the role of metallicity in stellar evolution through observations of massive stars in clusters in the Milky Way and the Large and Small Magellanic Clouds (LMC and SMC, respectively). This included observations of several hundred B-type stars, enabling detailed quantitative analyses of their physical parameters, particularly their abundances and rotation rates. It also observed tens of more-massive O-type stars, which was sufficient for a first investigation of the global scaling of their properties with metallicity. However, the "OB Zoo" is very diverse, with O-type stars spanning wide ranges in temperature (30 to 55 kK) and mass (15 to 100 $M_{\odot}$). A bigger observational sample was required to understand their evolutionary pathways.

Tarantula Nebula: A field of superlatives

As the most luminous star-forming region in the Local Group, the Tarantula Nebula (30 Doradus) is an immense stellar nursery where we can efficiently study several hundred O-type stars. It is located in the eastern part of the LMC, along with SN1987A and several slightly older clusters, at a distance of 50 kpc and with relatively little foreground extinction. The metallicity of young stars and interstellar gas in the LMC is approximately 50% solar, so observations of massive stars in 30 Dor allow us to investigate stellar evolution in an environment closer to that in star-forming galaxies at, and before, the peak of cosmic star formation.

To obtain an unprecedented spectroscopic sample of massive stars in 30 Dor, the VFTS consortium was formed in 2008 and secured 160 h of time with FLAMES (ESO Programme ID 182.D-0222). A previous Messenger article introduced the survey and some of the first results (Evans et al., 2011). In brief, 893 targets (with $V \leq 17$ magnitudes) were observed with nine different configurations of the FLAMES Medusa fibres (Figure 1). We used the LR02, LR03 and HR15N settings of the Giraffe spectrograph to cover the blue-visible range (396–507 nm, at $R \sim 7500$) and Hα (at $R \sim 16\,000$) to enable a quantitative spectroscopic analysis of each target. A key feature of the survey was a minimum of six repeat LR02 observations to look for radial-velocity shifts that might indicate the presence of binary companions. The majority of the observations were conducted in Period 82, with a final observation of each configuration in Period 84 to improve the detection of long-period binaries.

At the centre of 30 Dor is the massive young cluster R136, which is home to the most massive stars known to date (WNh stars with masses well in excess of 100 $M_{\odot}$). R136 subtends just a few arcseconds on the sky, so is unresolved by (seeing-limited) ground-based observations. To investigate the velocity dispersion of massive stars in and around R136, we therefore also obtained observations with the Fibre Large Array Multi Element Spectrograph (FLAMES) ARGUS integral-field unit (see Figure 1 from Evans et al., 2011). In parallel to the VFTS, consortium members have obtained HST ultraviolet and optical spectroscopy of the resolved population of R136, as well as more recent VLT observations with MUSE. These related projects were discussed by Crowther (2019) in a wider review of 30 Dor.

The VFTS quickly revealed an exceptional population of massive stars in the region, including runaway stars of up to 100 $M_{\odot}$ (VFTS 016, 072), a very massive (~ 150 $M_{\odot}$) WNh star in apparent isolation (VFTS 682), the fastest-rotating stars known (VFTS 102, 285), one of the most massive O-type binary systems (R139), the most massive overcontact binary known (VFTS 352), and a puzzling high-mass X-ray binary (VFTS 399).

Discovering these extremes of the population provides unique tests of our theories of stellar evolution, but the real breakthrough of the VFTS is the homogeneous dataset for over 700 O- and early B-type stars, i.e., the "normal" population. The VFTS series of over 30 papers[1] has analysed their physical properties (temperatures, gravities, mass-loss rates, rotation rates, chemical abundances), radial velocities (to investigate binarity)

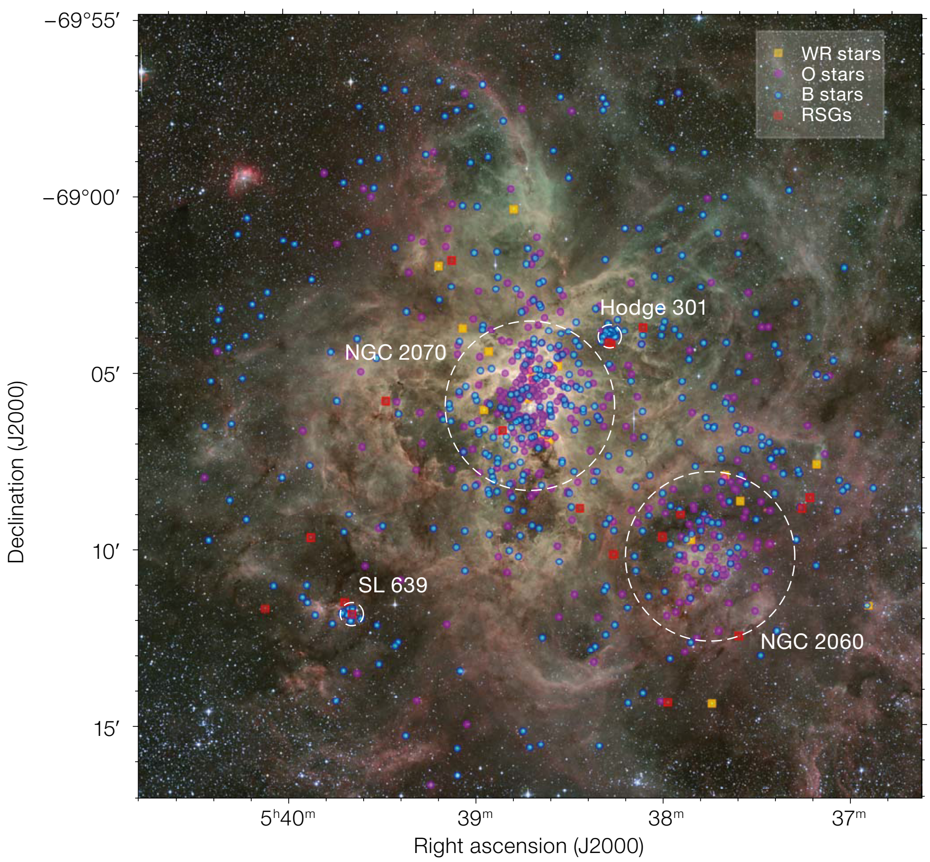

Figure 1. VFTS targets overlaid on the ESO RGB image of 30 Doradus obtained with WFI on the 2.2-m MPG/ESO telescope at La Silla. The dashed white circles highlight the four clusters in the region.

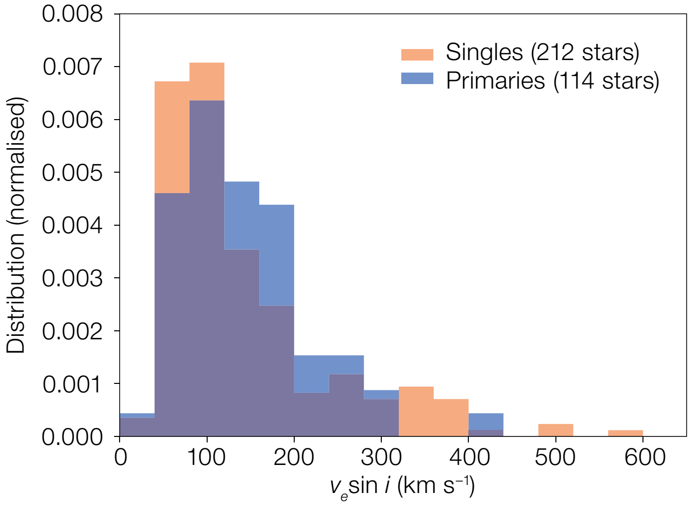

Figure 2. Projected rotational velocities ($v_e \sin i$) from the VFTS for single O-type stars and for O-type primaries of binary systems.

and interstellar gas. Alongside this work, several follow-up VLT programmes have further extended the impact of the VFTS, as well as related programmes with HST and Chandra.

We now briefly summarise some of the key results from the VFTS that have only been made possible by having such a large sample for the first time. We then highlight the serendipitous discovery of massive runaway stars from the region.

Binaries: most O-type stars are in multiple systems

The VFTS was designed to detect potential binary systems. The cadence of the observations varied, from data taken on the same or consecutive nights, to others that were several weeks apart, plus an additional epoch a year after the survey started. By modelling the observational completeness of the cadence for each field we estimated that we should detect 90% of systems with periods of 1 to 10 days, ramping down to ~ 70% at periods of 100 days, and with a steeper decline beyond that.

From the observed spectra, we found that 35 ± 3% of the O-type stars and 25 ± 2% of the B-type stars have evidence for at least one companion. Using synthetic populations to model our observational sampling and potential biases we estimated the intrinsic rates of binarity as 51 ± 4% (O stars) and 58 ± 11% (B stars). These results were consistent with the incidence of binarity seen in massive stars in the Milky Way. Moreover, with more than 50% of the O stars in 30 Dor expected to undergo mass transfer in the future, this further highlighted the importance of binary interactions in massive-star evolution.

Detailed characterisation of the orbital parameters of each detected system requires a larger number of observations (≥ 20). The cadence of our spectroscopy was sufficient to enable this for a few systems, but further monitoring was required for most of the sample. This motivated two follow-up programmes with FLAMES: the Tarantula Massive Binary Monitoring (TMBM) programme to characterise the majority of the detected O-type systems (PI: Sana; ESO Programme IDs 090.D-0323 and 092.D-0136) and the B-type Binaries Characterisation (BBC) programme for the B-type systems (PI: Taylor; ESO Programme ID 096.D-0825).

Results from the TMBM confirmed the similarity of the orbital properties with Galactic O-type systems, and preliminary results for the B-type systems suggest a similar distribution of orbital periods (Villaseñor et al., in preparation). These results demonstrate that binarity remains an important factor at the reduced metallicity of the LMC, and needs to be considered in, for example, population-synthesis models of distant Lyman-break galaxies.

The VFTS has also provided new empirical constraints on binarity in a very different part of the Hertzsprung-Russell diagram. By not imposing colour cuts on the target objects, we had also observed luminous, cool supergiants in 30 Dor. As the progenitors of type II-P supernovae, there has been considerable interest in red supergiant stars over the past decade. Red supergiant stars have radii that are hundreds of times larger than the Sun's, so we expect short-period binary systems to interact and/or merge before one of the components reaches the red supergiant phase. Nonetheless, little was known of the binary properties of red supergiant stars and the VFTS data provided a serendipitous opportunity to investigate their status. We found an upper limit of 30% of the red supergiant stars showing evidence for a companion, significantly lower than the fraction found for the O- and B-type stars. From these data the VFTS also identified signatures

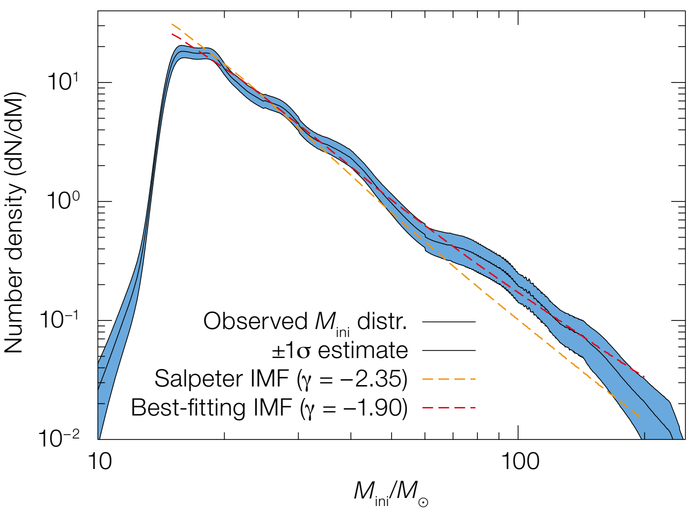

Figure 3. Initial mass (M_{ini}) distribution of the single stars more massive than 15 $M_{\odot}$ from the VFTS. A Salpeter IMF underpredicts the number of massive stars (particularly above 30 $M_{\odot}$).

of binary interaction products in the red supergiant phase (i.e., red stragglers).

Rotation: fast but not that fast

Rotation in massive stars became a standard ingredient of evolutionary models at the turn of the century and it can have significant effects on a star's evolution. For instance, rotationally induced mixing can bring fresh hydrogen into the core, extending the main-sequence lifetime, while also moving chemically processed material into the outer layers, thus changing the photospheric abundances.

A first step toward testing the predictions of rotating models is to determine present-day rotation rates of massive stars. The VFTS has enabled us to do this for the first time for > 300 O-type stars where their binary status is well characterised. We first investigated the projected rotational velocities ($v_e \sin i$) of 216 apparently single O-type stars and found a peak at around 80 km s^{-1} with an extended tail to high velocities (reaching as fast as 600 km s^{-1} in VFTS 102 and 285). We argued that the high-velocity tail may be primarily, if not exclusively, comprised of stars following binary interaction, in particular spin-up via mass transfer or merger. This hypothesis was supported by a relative dearth of rapid rotators ($v_e \sin i$ > 300 km s^{-1}) in a similar analysis of the 114 O-type binaries in the VFTS (Figure 2). In short, if an apparently single O-type star is found with very rapid rotation (> 300 km s^{-1}), it is probably the product of earlier binary interaction.

These results demonstrate typical current projected velocities of the O-type stars are around 100 km s^{-1}, with similar values found in the Galaxy (Howarth et al., 1997; Simón-Díaz & Herrero, 2014; Holgado et al., in preparation). The evolutionary tracks often used to investigate the wider impact of rotation (for example, on supernova yields) generally have initial rotation rates of 200–300 km s^{-1}. Such stars will slow down somewhat during the main sequence phase (via mass loss) but the spin-down is not sufficient to reach the observed velocities from the VFTS within their estimated lifetimes. Projection effects play a role, but deconvolution of the VFTS results to estimate v_e does not

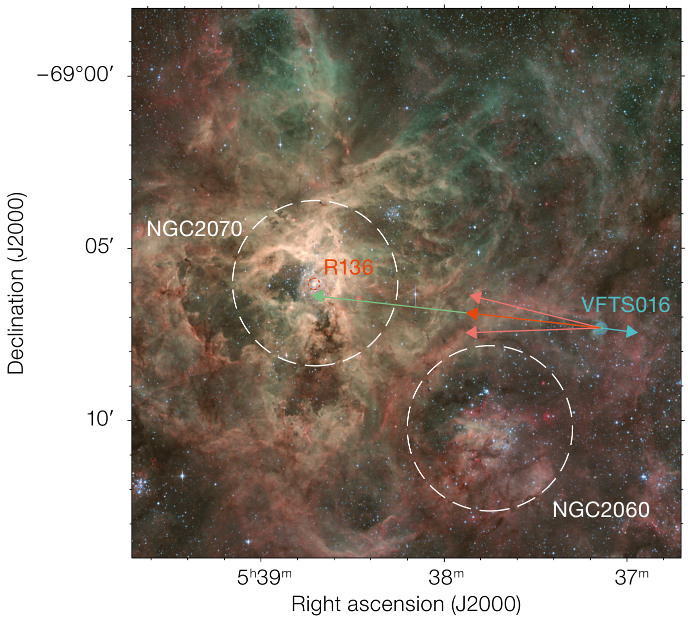

Figure 4. The Gaia proper motion for VFTS 016 confirms it as an apparent runaway from R136 but reveals an intriguing puzzle about its age. The dashed circles highlight the two main clusters, with R136 at the core of NGC 2070. Coloured arrows: *cyan*: direction of the Gaia proper motion; *green*: projection back to R136 (1.5 Myr at current space velocity); *red*: distance travelled for its estimated age from the VFTS (0.7 Myr); *pink*: opening angle given the Gaia uncertainties.

significantly change the peak value. The effects of rotation are increasingly important at faster velocities, so stars with v_e ~ 100 km s^{-1} do not spin down by much after formation and evolve quite similarly to stars without rotation. In short, rotation has been invoked to explain many characteristics (for example, enhanced mass-loss, and surface CNO abundances) but the VFTS results argue that these effects are most relevant only in a minority of main-sequence O-type stars. Conversely, the effects of rotation will play a significant role in the future evolution of mass-gaining stars in binaries.

Initial Mass Function (IMF): too many O-type stars in 30 Dor

Following quantitative analysis of the different subsets of the survey, we then took an overall look at the star formation history of 30 Dor. We used the BONN Stellar Astrophysics Interface (BONNSAI)[2] to obtain probability distributions of stellar masses and ages for the apparently single stars in the VFTS. The formation of massive stars in 30 Dor appears to have accelerated significantly 8 Myr ago, with the oldest stars located in the field, followed by the birth of those in NGC 2060 and NGC 2070 (Figure 1) and the formation of R136 being the most recent (although excluded from the VFTS sample, see Bestenlehner et al., in preparation). The origins of the field stars remain unclear. The timescales would have to be very short for them to have originated from dispersed clusters, and such a scenario is hard to reconcile with retention of the large molecular clouds that were required for the formation of the clusters we see today. In combination with our results from the VLT, the Gaia DR3 release should provide further constraints on the star-formation history of this important reference region.

Given the estimated uncertainties in the derived parameters of each star, BONNSAI also returns a probability distribution for the initial stellar mass, enabling the study of the initial mass function (IMF) in 30 Dor with an unprecedented sample (Schneider et al., 2018). The IMF is well populated up to 200 $M_\odot$ with 76 stars having M_{init} > 30 $M_\odot$, an excess of 18 ± 7 stars compared to the expected number for a Salpeter IMF (with a power-law slope of $\gamma = 2.35$). Fitting the slope of the initial mass distribution of the full sample in 30 Dor with a similar power-law gives a shallower slope of $\gamma = 1.90^{+0.37}_{-0.26}$ (Figure 3).

Even a modestly shallower slope in a rich region such as 30 Dor can have a tremendous impact on the expected feedback from the massive-star population compared to models that assume a Salpeter slope. For instance, assuming an upper mass limit of 200 $M_\odot$, the number of core-collapse supernovae increases by 70% (giving a threefold boost in the metal yields), the ionising radiation is ~ 3.5 times greater, and the formation rate of black holes is almost three times larger.

We add that stars with masses > 100 $M_\odot$ have typically not been included in population-synthesis models of star-forming galaxies but are found to contribute at least a quarter of the overall feedback (ionising photons, wind momentum) from 30 Dor (including R136). The combination of strong nebular emission and potential leakage of Lyman-ionising photons suggests that 30 Dor is a local example of conditions in the so-called Green Pea galaxies that have intense star-formation rates and that, it has been suggested, play a role in the reionisation of the early Universe (see Crowther, 2019 for further discussion).

Runaway surprises from R136

The power of the VLT to yield unexpected discoveries is highlighted by the massive runaway stars found by the VFTS. This topic was not envisaged in the initial proposal but has been the subject of several papers in the series and has grown in importance given the increased focus on binary evolution and compact objects.

One of the first results from the survey was the discovery of a massive (~ 90 $M_\odot$) O2-type star, VFTS 016, some 120 pc in projection from R136 on the western periphery of 30 Dor. The multi-epoch VFTS spectroscopy revealed its radial velocity to be discrepant compared to the local population (by approximately 85 km s^{-1}, confirmed by older spectra from the Anglo-Australian Telescope). Critically, no radial-velocity shifts were seen in the spectra, suggesting that VFTS 016 is a single, runaway star.

There are two theories accounting for the ejection of runaway stars from star-forming regions: either via dynamical interactions in a cluster or the “kick” from a supernova explosion in a binary system. We usually lack constraints on which mechanism is responsible. The particular interest in VFTS 016 is that R136 is only 1–2 Myr old, such that its members are still too young to have exploded as supernovae. Thus, if VFTS 016 originated from R136 it is a strong contender for dynamical ejection.

An image was released alongside the original paper (prepared by Zolt Levay and the STScI outreach team)[3], which highlighted the possible direction of VFTS 016 away from R136. Only with the tremendous power of the Gaia mission have we finally been able to test the origins of VFTS 016; its proper motion satisfyingly points almost radially away from R136 (Lennon et al., 2018; Figure 4).

Given the current proper motion of VFTS 016, the time-of-flight estimate from R136 to its current position is 1.5 ± 0.2 Myr. This is compatible with the age of R136, suggesting the star was ejected early in the life of the cluster. However, this star has presented a new puzzle as its best age estimate from spectroscopic analysis is 0.7 ± 0.1 Myr, contrasting with the dynamical value. Indeed, if it were much older than 0.9 Myr, it should be several thousand degrees cooler.

Gaia also revealed a second massive O2-type runaway star (VFTS 072) on the outer fringes of 30 Dor (Lennon et al., 2018), with a similar tension between the ages from its inferred time-of-flight and from spectroscopic analysis. These results argue that these objects have perhaps had more unusual evolutionary histories than perceived at first glance (for example, merger products after dynamical ejection), or that there is something fundamental still missing from our understanding of evolutionary and/or atmospheric models at the highest masses and temperatures.

The VFTS has found other, less massive, candidate runaways from spectral-classification and radial-velocity arguments. Work is now under way to estimate their proper motions from a multi-epoch HST programme (PI: Lennon) and our team is keenly awaiting the Gaia DR3 release. In particular, both HST and Gaia Data Release 2 (DR2) results for the 150-$M_\odot$ star VFTS 682 suggest that it might also have been ejected from R136, but further observational constraints are required to be sure of its origin.

Figure 5. The VFTS consortium in Edinburgh in May 2019.

Reflections and future directions

The most recent consortium meeting was held in Edinburgh in May 2019 (Figure 5), and from the enthusiastic discussions it was clear that the field is even more vibrant and topical than when we started. The close collaboration between observation and theory throughout the project has been particularly rewarding. Many theory papers by consortium members have been published in parallel with the VFTS series, drawing on our results and cross-fed by ideas from consortium meetings. Moreover, VFTS papers led by PhD students have directly contributed to a dozen theses across the consortium.

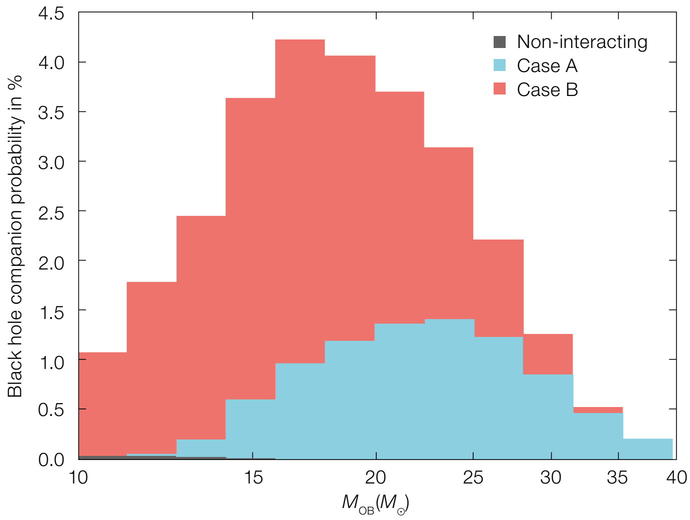

Figure 6. Probability that OB-type stars of a given mass in the LMC have a black hole companion, as a function of the mass of the OB star (Langer et al., 2020). This prediction suggests there should be many massive black holes waiting to be discovered in binaries in the LMC.

The Magellanic Clouds will continue to be our primary windows on the low-metallicity universe for observers and theoreticians alike. The Edinburgh meeting helped focus priorities for the coming years, and ESO facilities such as the VLT and 4-m Multi-Object Spectrograph Telescope (4MOST)-VISTA will have a major role to play in addressing some of the key scientific questions for the community, for example:

– An ambitious spectroscopic survey of massive stars in the SMC (including constraints on their multiplicity). This would enable critical tests of massive-star evolution at lower metallicity rather than extrapolating from the current Galactic and LMC results. It would also help us to investigate the potential progenitors of unexplained spectacular explosions such as superluminous supernovae that are seen in (metal-poor) dwarf galaxies, as well as stellar evolution at high redshift, where low metallicity is more typical and where GW detectors are discovering massive merging black holes.
– The ULLYSES Director's Discretionary programme with HST is under way and will provide new ultraviolet spectroscopy of around 170 massive stars in the Magellanic Clouds, enabling determination of their wind properties (for example, terminal velocities, mass-loss rates, clumping). Complementary optical/near-infrared spectroscopy with the VLT will play an important role in maximising the scientific impact from ULLYSES.

Beyond the Magellanic Clouds, observations of massive stars in the lowest-metallicity systems known (< 10% solar) are also an area of significant interest (for example, in the Sagittarius Dwarf Irregular Galaxy, Sextans A and Leo P). Probing such systems well beyond the Local Group will require the spectroscopic grasp of the ELT (with, for example, the MOSAIC multi-object spectrograph) and a future large-aperture ultraviolet mission (for example, the LUVOIR concept studied as part of the US Decadal process).

The VFTS observations have been essential to improving structure and evolution models of massive stars, with follow-up studies providing further key data to address uncertainties in models of binary stars. An important first test of the predictions of stellar evolution at sub-solar metallicity was to focus on the properties of OB-type stars with black hole companions in the LMC (Langer et al., 2020). Black hole companions were predicted in ~ 3% of the late O- and early B-type stars (Figure 6), but of the predicted ~ 100 massive black hole binaries in the whole LMC, we know only one (LMC-X1). We are now therefore redoubling our efforts to find them, as they (or their absence) will provide a critical test of the models. Our work continues.

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Links

[1] VFTS papers: https://ui.adsabs.harvard.edu/public-libraries/RWpc6wl9ShKVYYqyYVJlyg
[2] BONNSAI tool: https://www.astro.uni-bonn.de/stars/bonnsai/
[3] News Release: Hubble catches runaway star from 30 Doradus: https://hubblesite.org/contents/news-releases/2010/news-2010-14.html
[4] All of the reduced spectra from the survey are available at: https://www.roe.ac.uk/~cje/tarantula/spectra/

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NGTS — Uncovering New Worlds with Ultra-Precise Photometry

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The Next Generation Transit Survey (NGTS) is a state-of-the-art photometric facility located at ESO's Paranal Observatory. NGTS is able to reach a precision of 150 ppm in 30 minutes, making it the most precise ground-based photometric system in the world. This precision has led to the discovery of a rare exoplanet in the "Neptune Desert" (NGTS-4b), the shortest-period hot Jupiter ever discovered (NGTS-10b), and the first exoplanet recovered from a TESS monotransit candidate (NGTS-11b). It has also allowed NGTS to characterise exoplanet candidates transiting very bright stars ($V < 10$) from the TESS mission, and to make coordinated observations in support of VLT programmes.

Exploring other worlds

It has been a quarter of a century since the ground-breaking discovery of 51 Peg b (Mayor & Queloz, 1995) brought the field of exoplanet research to life. As we continue to discover exoplanets in ever greater numbers, the challenge is now to try to understand the astounding diversity of these worlds, many of which have no analogues in our own Solar System. The Next Generation Transit Survey[1] (NGTS; Wheatley et al., 2018) is at the forefront of this effort, finding and characterising transiting exoplanets around bright stars.

The NGTS facility

The NGTS facility is a set of twelve fully robotic and automated 20-cm telescopes located at the Paranal Observatory in Chile (see Figure 1). Housed in a single roll-off roof enclosure just under 2 km from the VLT, NGTS was built at Paranal Observatory to take advantage of the site's excellent photometric conditions. All aspects of the NGTS design, from the ultra-stable telescope mounts to the high-quality CCD cameras, were tailored to ensure NGTS would deliver the highest possible photometric precision. Such precision is needed to detect the tell-tale dip in a star's brightness caused by an exoplanet passing in front of it. NGTS is sensitive to detecting dips of just 0.1%, which equates to a Neptune-sized planet transiting a Sun-like star.

NGTS began science observations in April 2016 (West et al., 2016) and for

Figure 1. The twelve NGTS telescopes at dusk, just about to begin nighttime operations. The NGTS facility is located at ESO's Paranal Observatory in Chile. The VLT can been seen in the background.

M. Garlick & University of Warwick

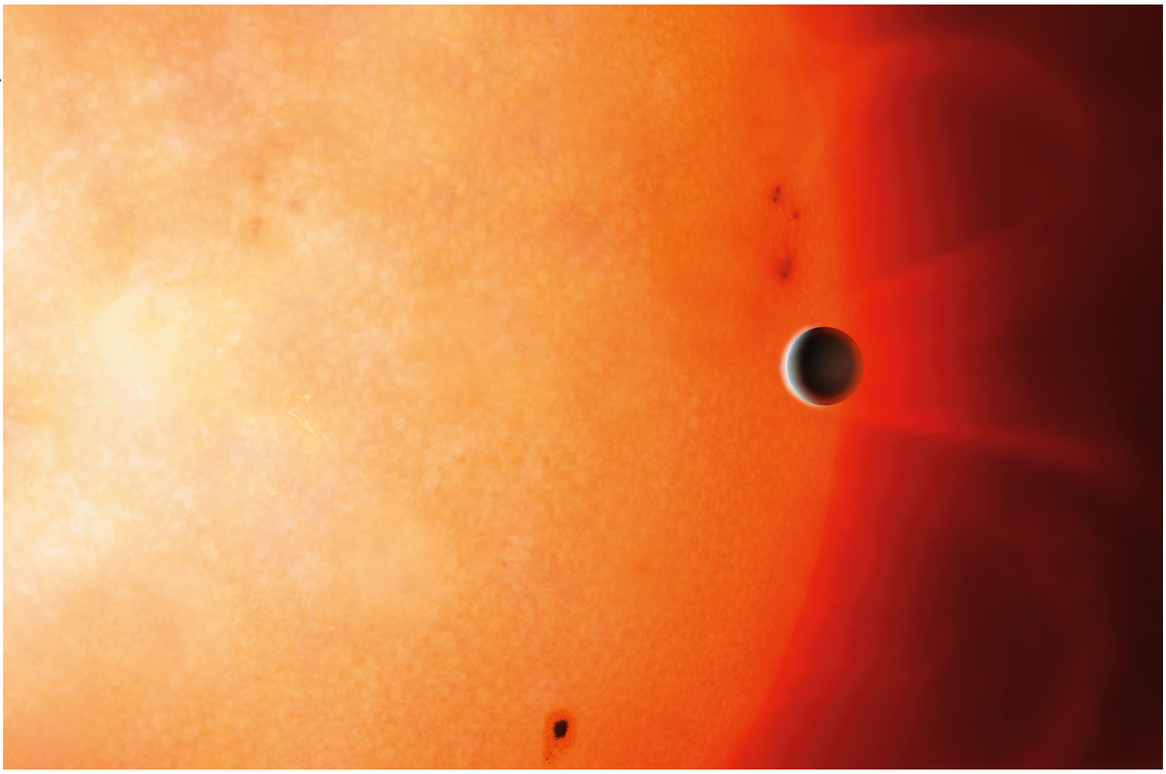

Figure 2. Artist's impression of NGTS-4b, a Neptune-sized exoplanet in the "forbidden" zone around its host star.

the past four years NGTS has been surveying the southern skies for transiting exoplanets around bright stars. In this article we highlight some of the key discoveries from NGTS and outline the exciting future we envisage for exoplanet science with NGTS.

The "forbidden" planet — NGTS-4b

The high photometric precision of the NGTS facility has allowed us to discover rare objects that were not visible to previous ground-based exoplanet surveys. One such example is NGTS-4b, a Neptune-sized planet orbiting a bright K-dwarf star (West et al., 2019; see Figure 2). The transit of NGTS-4b is just 0.13% deep, far shallower than that of any planet previously discovered from ground-based photometry. This breakthrough demonstrates the ability of NGTS to discover exoplanets that present only very shallow transits in our time-series photometry.

NGTS-4b orbits its host star in just 1.34 days and is thus subject to relatively strong irradiation. Previously, the Kepler survey (Borucki et al., 2010) revealed that Neptune-mass planets are not found this close to their host stars (Mazeh, Holczer & Faigler, 2016), the region being called the "Neptune Desert". The likely cause of the lack of short-period Neptune-mass planets is that these planets are not massive enough to retain their H/He atmosphere in such a high-radiation environment. So, over time, they would evaporate away to become the much smaller "super-Earth" planets that are found in great abundance by Kepler.

However, NGTS-4b does not fit this picture. Radial velocity measurements made using the High Accuracy Radial velocity Planet Searcher (HARPS) instrument on the ESO 3.6-m telescope reveal that the mass of NGTS-4b is just 20 $M_{\oplus}$, so we would not expect it to be able to retain its

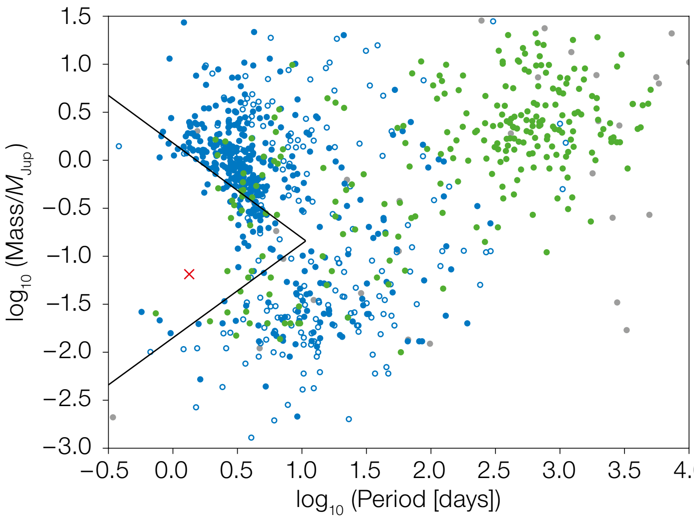

Figure 3. The distribution of exoplanet masses and orbital periods, showing a dearth of Neptune-mass planets in short-period orbits. The "Neptune Desert" is the region interior to the solid black lines. Exoplanets are colour-coded by discovery method: transit (blue), radial velocity (green) and other methods (grey). Exoplanets with masses measured to better than 30% are represented as filled circles. NGTS-4b (red cross) stands out as being well inside the Neptune Desert. Figure from West et al., 2019.

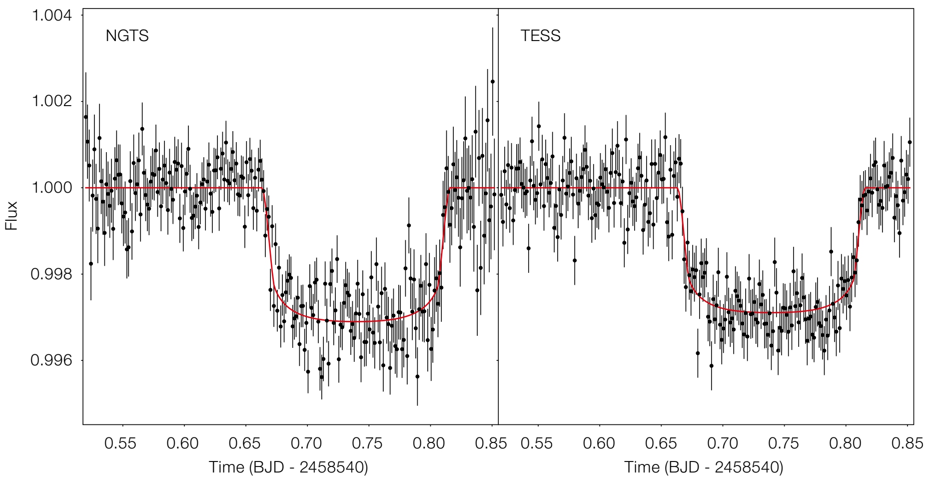

Figure 4. The transit of WASP-166b on the night of 25 February 2019. The data on the left are from the combination of nine NGTS telescopes (binned to two minutes). The data on the right are the TESS space telescope observation of the same transit event at a two-minute cadence. The red line is a best-fit transit model to the data. NGTS achieved an average photometric precision of 150 ppm across the transit event — a similar precision to that of TESS. Figure from Bryant et al., 2020.

atmosphere so close to its host star. It lies almost in the middle of the Neptune Desert — a "forbidden" planet! (see Figure 3). Given that there is no indication that NGTS-4 is a particularly young star, it is surprising to find an exoplanet like NGTS-4b, and its existence presents an opportunity to unravel the processes that control planetary evaporation.

The shortest-period hot Jupiter ever found: NGTS10b

Another rare planet that NGTS has recently uncovered is the ultra-short-period NGTS-10b (McCormac et al., 2020). Incredibly, NGTS-10b orbits its host star in just 18 hours, making it the shortest-period gas giant planet ever found. Being this close to its host star, NGTS-10b is expected to be undergoing rapid inspiral as a result of tidal orbital decay. The predicted lifetime of NGTS-10b is just 40 Myr, making it a very fortuitous find indeed. The predicted inspiral rate is estimated to be on the order of 7 seconds over a decade, which is potentially detectable. This inspiral rate is strongly dependent on the planet's tidal quality factor (Q_P), which is currently highly uncertain for giant exoplanets. We have initiated a long-term project on NGTS in order to try to measure tidal orbital decay on NGTS-10b and other ultra-short-period gas giants.

The discovery of NGTS-10b highlights two key advantages that NGTS holds over other transit surveys, such as NASA's Transiting Exoplanet Survey Satellite (TESS). Firstly, NGTS imaging is carried out at a very high time cadence — approximately 13 seconds per image. This allows us to fully resolve the transit event, even for systems like NGTS-10b where the transit is just one hour in duration. Such events are not well resolved with the 30-minute cadence of Kepler or TESS full-frame imaging. Secondly, the spatial scale of the NGTS imaging is four times finer than that of TESS, allowing us to resolve many neighbouring stars that would be blended in TESS imaging. NGTS-10 happens to be located just 40 arcseconds from a very bright star (V = 9.32), which would result in highly blended photometry in most other wide-field transit surveys.

The first discovery from a TESS monotransit: NGTS-11b

One of the primary limitations of using the transit method to discover exoplanets is that it is extremely biased towards finding very short-period exoplanets. This potentially leaves a wealth of longer-period planets hidden. Crucially, the longer-period planets that most transit surveys miss include planets in the so-called "habitable" zone of the host star — the zone within which liquid water could exist on the surface of an exoplanet. We are therefore eager to extend the reach of transiting planet surveys towards these longer-period planets, and the NGTS team is doing this via "monotransits" from the TESS mission.

A monotransit occurs when only a single transit is present in the duration of the photometric monitoring of a star. Monotransits are common in the TESS data, since most stars are only monitored for approximately 27 days. Simulations show that we can expect over 1000 monotransit events from a single year of TESS data (Cooke et al., 2018). However, there are two large stumbling blocks when working with these monotransits. First, with only a single event in the photometric data, the chance that the signal is a false alarm is far higher than normal. Second, even if the event is a real astrophysical signal, with only a single transit we cannot determine the orbital period of the planet or predict the next transit. It is therefore extremely difficult to discover transiting planets based on monotransits in the TESS data.

To overcome these difficulties, the NGTS team has set up a project to carefully sift through the TESS lightcurves to detect monotransits, and then to schedule the candidates on to individual NGTS telescopes for further monitoring. We focus on TESS monotransit candidates from giant planets transiting bright stars. This project fits in well to our regular NGTS monitoring programme, the only difference being that field positions are selected to include the TESS monotransit candidates.

Our first three successful recoveries were TOI-222 (Lendl et al., 2020), TIC-238855958 (Gill et al., 2020a) and TIC-231005575 (Gill et al., 2020b) with periods of 33.9 days, 38.2 days, and 61.8 days, respectively. In all cases radial velocity measurements revealed that, although the transiting objects were similar in size to gas giant exoplanets, they were actually very low-mass stars (0.1 to 0.2 $M_{\odot}$). These very low-mass stars are interesting in their own right, as precise masses and radii have been measured for only a handful of such stars. These discoveries complement the NGTS studies into other low-mass star systems, such as our discoveries of low-mass companions to M-dwarf stars (Casewell et al., 2018; Acton et al., 2020).

On the night of 24 October 2019, after monitoring the field for 80 nights, NGTS detected another transit around a TESS monotransit candidate. The detected transit matched the depth and duration of the TESS transit, but there was over a year between these two transit events. This left us with a set of 13 possible periods for the system. Radial velocity measurements from HARPS on the ESO 3.6-m telescope revealed that the true orbital period was 35.5 days, and that this time NGTS had detected an exoplanet, named NGTS-11b, with a mass of 0.34 M_{Jup} (Gill et al., 2020c). NGTS-11b is the first exoplanet to be discovered from a TESS monotransit event!

With an orbital period of 35.5 days, NGTS-11b is a transiting giant planet with one of the longest periods found to date. The equilibrium temperature of NGTS-11b is just 435 K, and it therefore presents an opportunity for future atmospheric transmission spectroscopy with the wide range of ESO instrumentation able to probe an exoplanet atmosphere much cooler than those of typical transiting gas giants (> 1000 K). Figure 5 shows the irradiating flux received by NGTS-11b compared with other transiting planets, demonstrating the unique nature of this exoplanet.

Many telescopes make light work

In typical survey mode, the NGTS telescopes each observe a different area of the sky searching for transiting exoplanets. However, the design of NGTS makes it possible for several telescopes to simultaneously observe a single star. For bright stars (V < 10), where scintillation is the dominant source of photometric noise, this is especially beneficial since the scintillation noise is independent for each telescope. As a result, by combining multiple NGTS telescopes, we are able to increase our photometric precision. Early testing of this operation mode in 2017 was very promising, with a multi-telescope observation capturing the 0.1% transit of HD 106315c (Smith et al., 2020).

To further study the potential of this new mode of operation, we used nine NGTS telescopes to observe a transit of WASP-166b simultaneously with the TESS spacecraft. WASP-166 is a bright (V = 9.3) F-type dwarf star which hosts a transiting exoplanet in a 5.4-day orbit (Hellier et al., 2019). The exoplanet is very inflated — it is about twice the mass of Neptune but has a density less than half that of Jupiter. The transit is only 0.3% in depth, so presents a challenging target for ground-based facilities.

By combining nine NGTS telescopes, we were able to achieve a photometric precision of 150 parts per million (ppm) on a 30-minute timescale (Bryant et al., 2020). Such precision was previously the preserve of space-based photometry such as the TESS mission (Ricker et al., 2015). Since we observed the transit simultaneously with TESS, we are able to directly compare our lightcurve to the TESS lightcurve — which we show in Figure 4. NGTS reaches a precision similar to that of TESS for this target.

The power of using multiple NGTS telescopes in this coordinated manner is now being utilised to undertake critical photometric observations for discoveries of exoplanets around bright stars. Already, NGTS multi-telescope photometry has contributed to some of the most exciting discoveries from the TESS mission, for example, TOI-849b, the remnant core of a giant planet (Armstrong et al., 2020) and LTT 9779b, the most highly irradiated Neptune-mass planet ever discovered (Jenkins et al., 2020). NGTS is pleased to make lightcurves of bright TESS candidates available to the community through its membership in the TESS Follow-Up Program[2].

Data for the community

All of the NGTS data are made publicly available to the community via the ESO archive[3]. The first NGTS data release was in November 2018 and consisted of 24 separate fields (each 2.8 × 2.8 degrees) completed during the first year of observations (April 2016 to April 2017). The data release includes a catalogue of the observed sources down to V = 16, together with the lightcurves and full-frame images. The data release contains lightcurves for over 200 000 sources, and in total equates to around 32 billion data points at a 13-second cadence.

The next NGTS data release (DR2) has just been released[4] and includes all survey fields completed by NGTS up to April 2018. The data release contains over 600 000 lightcurves and approximately 13 million individual full-frame images.

With the advent of multi-telescope observations, NGTS is now able to provide

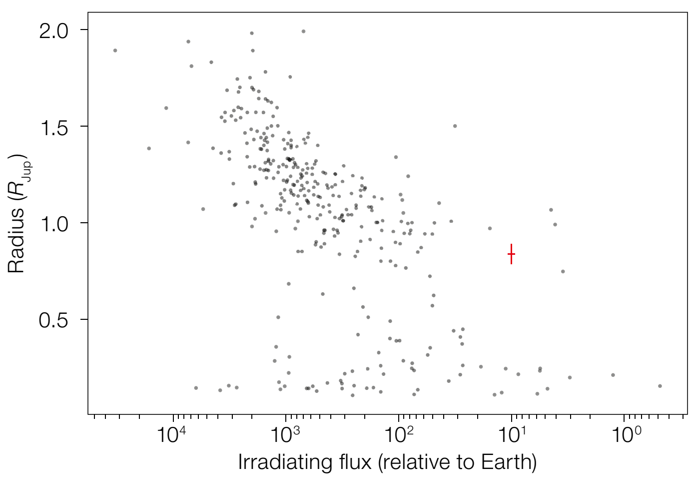

Figure 5. The irradiating flux for well characterised transiting planets (black circles) and NGTS-11b (red cross) in units of irradiation received by the Earth. NGTS-11b is one of the least irradiated transiting gas giant exoplanets known. Figure from Gill et al., (2020c).

photometry at a level of ~ 150 ppm for selected bright stars. Given that the NGTS telescopes are located at Paranal Observatory, we have also started coordinated photometric monitoring of stars to aid observations from instruments such as the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO) on the VLT. Figure 6 shows one such coordinated campaign, where NGTS monitored the star WASP-52 in order to measure the stellar activity to support ESPRESSO transit spectroscopy. NGTS welcomes collaborations with any VLT users who would find it useful to acquire coordinated high-precision photometry of their bright star targets.

In addition to exoplanet science, NGTS is making important contributions to stellar astrophysics, particularly with respect to young stars and stellar flares. As part of our young open cluster monitoring programme, we observed the Blanco 1 cluster over 200 days and determined rotation periods for 127 stars, which provided new insights into the angular momentum evolution of FGKM stars at approximately 100 Myr (Gillen et al., 2020). NGTS imaging is also being used to study stellar flares at a high time cadence, which has led to a number of important discoveries including the first detection of a white-light flare from an ultracool L2.5 dwarf star, an event which briefly caused the star to brighten by 6 magnitudes (Jackman et al., 2019).

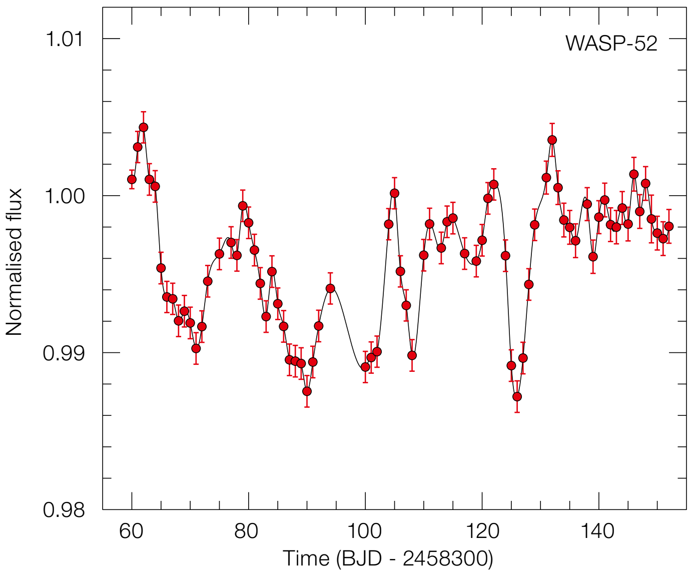

Figure 6. Long-term NGTS monitoring of WASP-52. The NGTS photometric points (red points) and a cubic spline (black solid line). The NGTS photometry is able to map out the spot activity for WASP-52, aiding in the interpretation of three spectroscopic transits of WASP-52b observed by ESPRESSO during this time period.

A bright future

NGTS has now been operating for over four years and is producing photometry for bright stars that is on a par with space-based photometry. Over the coming years, NGTS will be at the forefront of exoplanet discoveries for both bright planet-hosting stars and for longer-period transiting planets.

Acknowledgements

We acknowledge the generous in-kind support from ESO, including support and advice from individual ESO staff members, which has been crucial for the construction and ongoing operation of the NGTS facility.

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Links

[1] NGTS Webpage: https://ngtransits.org/
[2] TESS Follow-Up Program: https://tess.mit.edu/followup/
[3] NGTS DR2: http://archive.eso.org/scienceportal/home
[4] Documentation: http://eso.org/rm/api/v1/public/releaseDescriptions/154

Screenshots from virtual tours of the La Silla and Paranal Observatories which are being held regularly on ESO's Facebook and YouTube channels in English and in Spanish so that you can acquaint yourself with these world-leading facilities despite the current travel restrictions related to the pandemic.

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The ESO Cosmic Duologues

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On 26 April 1920, Harlow Shapley and Heber Curtis engaged in a debate on the scale of the Universe which became known as the Great Debate. That event continues to be seen as an exemplary way of addressing controversies, particularly in astronomy. While, after 100 years, many (if not all) of the scientific questions raised during the Great Debate have been answered, it is a common feature of research that as one question is answered new and often unexpected questions show up. Inspired by these considerations, ESO decided to commemorate the Great Debate with a series of events called the ESO Cosmic Duologues.

Since early this year, the world has had to face extreme challenges caused by the COVID-19 pandemic. These circumstances have had drastic and often tragic consequences for many people around the world. Cities have experienced varying degrees of closure of commercial and social activities, while for long periods of time, citizens have been asked to maintain social distancing measures and to essentially live in confinement in their own homes. Academia and research have of course also been affected, with scientists forced to continue their work through teleworking or remote working arrangements, including quickly having to arrange online lectures and courses in many educational institutions. Most of the planned international conferences, science events, seminars and collaborative meetings have been postponed, if not cancelled, except in the few cases where arrangements could be made to move them online.

At ESO we felt a responsibility to find creative outlets at this time to help maintain and further develop scientific interactions, and to ignite curiosity around some of the biggest questions in astronomy today — attempting to address humanity's need to understand its surroundings.

We feel it is important from time to time for scientists to leave their, often narrow, field(s) of specialisation to revisit some of the main hypothesises or assumptions that underpin today's astronomical research: for example, is MOND a viable alternative to the standard Lambda-Cold-Dark-Matter model (ΛCDM)? Do intermediate-mass black holes exist and is the question even relevant? What is really meant by the stellar initial mass function? Are rings in discs around young stars really signposts of planets?

A series of live web events

The Great Debate of Shapley and Curtis (Curtis, 1921 and Shapley, 1921) itself follows a model set much earlier by Galileo Galilei in his book Dialogo — or in English, Dialogue Concerning the Two Chief World Systems (Galilei, 1632) — which presented arguments as a dialogue between two philosophers and an intelligent layperson. In ESO's Cosmic Duologues this discussion is between two scientists, with a third scientist acting as moderator.

The Cosmic Duologue series started on 27 April 2020 and was held roughly every second week. The goal was to ensure a dialogue between two (hence "duologue") professional astronomers, each an internationally recognised expert in their field, moderated by an ESO astronomer (staff or Fellow), with the aim of shedding light on the current state of some of the major questions in astronomy. While the Shapley–Curtis debate was held at the Smithsonian Museum of Natural History in Washington, DC, the confinement measures forced us to organise the ESO Cosmic Duologues as a series of live web-based events.

Table 1 shows the agenda of the events, including the list of topics, the speakers and the moderators. We strove to involve young researchers and to ensure a good gender balance. These efforts were fairly successful, with a female representation among the speakers of 35% (5/14), and a corresponding 43% (3/7) fraction among the moderators.

Table 1. The agenda of the events. All the PDF files of the presentations, the recordings of the live events, and a brochure summarising the answers from the speakers to questions posted by attendees on YouTube's Live Chat are linked from the duologue webpages[1].

Date	Topic	Speakers	ESO Moderator
27 April 2020	Dark Matter and MOND	Azadeh Fattahi (Durham, UK), Federico Lelli (Cardiff, UK)	Steffen Mieske
11 May 2020	Intermediate Mass Black Holes: To be or Not to be?	Marta Volonteri (IAP, France), Tom Maccarone (Texas Tech University, USA)	María Díaz Trigo
25 May 2020	Initial Mass Function: Universal... or Not?	Tereza Jerabkova (IAC/GTC, La Palma, Spain; Bonn University, Germany), Andrew Hopkins (AAO Macquarie – Macquarie University, Australia)	Giacomo Beccari
8 June 2020	The formation and evolution of the Solar System	Megan Schwamb (Queen's University Belfast, UK), Sean Raymond (Université de Bordeaux, France)	Cyrielle Opitom
29 June 2020	Substructure in protoplanetary discs: a signpost of planet formation?	Edwin (Ted) Bergin (University of Michigan, USA), Alessandro Morbidelli (OCA, Nice, France)	Stefano Facchini
6 July 2020	Dust at high *z*	Marusa Bradac (UC Davis, USA), Andrea Ferrara (Scuola Normale Superiore, Pisa, Italy)	Paola Andreani
20 July 2020	The atmospheres of Exoplanets	Neale Gibson (School of Physics, Trinity College Dublin, Ireland), Jonathan Fortney (University of California Santa Cruz, USA)	Valentin Ivanov

Technical aspects

The duologues were hosted using the web-based video conferencing tool Zoom and live streamed on a dedicated YouTube channel[2]. The attendees at the live event were encouraged to ask questions and participate in the duologue

Figure 1. ESO Cosmic Duologues poster.

by posting their questions on the Live Chat on YouTube (or using a web form or by email if they preferred). All of the video recordings of the live events, including the content of the live chat, are available on YouTube. Links to the videos and the PDFs of the presentations are available on the duologue webpages[1].

Each event started with an introduction to the topic by the moderator, who sometimes also presented a few slides. The two speakers were then asked to each give a 20-minute talk on the topic, highlighting their perspective and vision on the current state of research in the area. In particular, the speakers were asked to place the focus on open issues in order to later engage in a dialogue aimed at emphasising the critical areas and open questions. After the two talks, the stage was opened for dialogue. The moderator was asked to keep an eye on the Live Chat in order to catch the questions coming from the attendees and pass them on to the speakers. At the same time, we monitored the dedicated email accounts and forwarded these questions via the Zoom platform to the moderator, together with any other input.

As shown in Table 1, the first duologue was about MOdified Newtonian Dynamics (MOND) versus dark matter. The discussion was between Azadeh Fattahi (Durham, UK) who spoke about dark matter and Federico Lelli (Cardiff, UK) speaking about MOND; it was chaired by Steffen Mieske (ESO). This topic is of the highest astrophysical interest, as the existence of dark matter has profound implications for the formation and evolution of galaxies at all redshifts, as well as for our understanding of galaxy dynamics. The atmosphere of the duologue was extremely pleasant, and the overall tone was professional and engaging.

This first event was streamed live on the YouTube channel[3] with almost 350 participants at its peak. In Figure 2 we show a snapshot of the event on YouTube. The attendees gave life to an animated discussion on the Live Chat, highlighting pros and cons of both theories. We were very pleased to witness the active participation of astronomers of all ages, career stages and genders. This event was proof that a virtual platform has the unexpected effect of breaking down physical barriers and can trigger a truly wide participation in the scientific discussion. It was particularly gratifying to note that the younger astronomers appeared less intimidated to engage with the speakers than they might have been in an auditorium setting. At the time of writing, this event has accumulated almost 2500 views on YouTube — quite a spectacular achievement for a professional event.

Ensuring a legacy

The positive, professional and cordial spirit in which all of the duologues were conducted was greatly appreciated by all

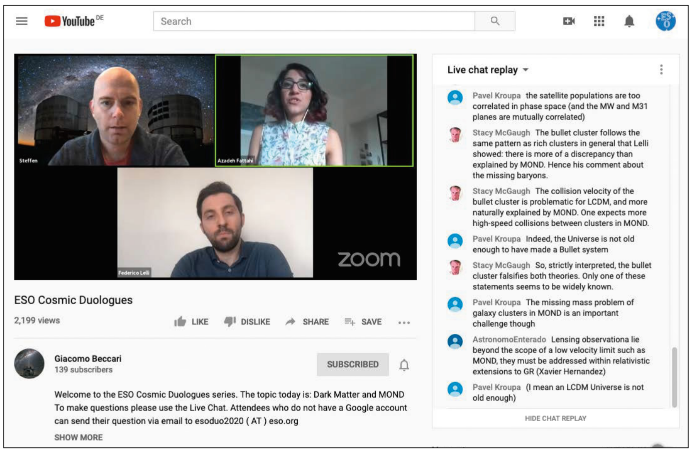

Figure 2. A snapshot from the live stream on YouTube of the first Cosmic Duologue entitled "Dark Matter vs MOND".

participants and attendees. The YouTube videos have already collected more than 6400 views in total and represent an invaluable resource to astronomers at all stages of their careers.

In order to provide the community with a summary of the most relevant and still open scientific questions raised during the duologues, we have collected some of them in a booklet. Each chapter is presented in the form of an interview with the speakers, who answer questions raised during the live events. While the entire booklet, which will include an introduction to each topic written by the moderator of the corresponding duologue, will be electronically published later in 2020, a draft of each chapter can be already downloaded from the dedicated page for the corresponding duologue.

In conclusion, the ESO Cosmic Duologues allowed us to engage with and reach the astronomical community under challenging circumstances with an original and lively series of scientific discussions centred around some of the most topical areas in astrophysics. We note that, as the rate of science productivity continues to escalate (as can be traced for example by the ever-increasing amount of data and numbers of papers and conferences), it is imperative to take a step back and reflect on some of the scientific assumptions that constitute the pillars of astronomical knowledge today.

Acknowledgements

We would like to thank all the speakers who accepted our invitation to participate in the ESO Cosmic Duologues. We are also extremely thankful to those who acted as moderators and invested their energy and creativity to make this series possible. We also acknowledge the support of the ESO Directorate for Science and the ESO Office for Science.

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Links

[1] Cosmic Duologue webpages: duo.eso.org
[2] Cosmic Duologue YouTube channel: youtube.com/channel/UC70TAbRgtfFobkWcmYFVS7w
[3] Dark Matter and MOND Cosmic Duologue: youtu.be/cuY-dgkenn4

A. Tyndall/ESO

People are enjoying the sunset on top of Cerro Paranal in Chile.

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A History of the Magellanic Clouds and the European Exploration of the Southern Hemisphere

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The Magellanic Clouds were known before Magellan's voyage exactly 500 years ago, and were not given that name by Magellan himself or his chronicler Antonio Pigafetta. They were, of course, already known by local populations in South America, such as the Mapuche and Tupi-Guaranis. The Portuguese called them Clouds of the Cape, and scientific circles had long used the names of Nubecula Minor and Major. We trace how and when the name Magellanic Clouds came into common usage by following the history of exploration of the southern hemisphere and the southern sky by European explorers — which ultimately led to the founding of ESO.

This year we celebrate the 500th anniversary of the discovery of the navigable sea route that separates mainland South America from Tierra del Fuego — now known as the Strait of Magellan — by Fernão de Magalhães (Ferdinand Magellan in English) and his companions. It therefore seems an appropriate time to examine the "history" of the Magellanic Clouds, not least because the study of the Clouds was one of the main reasons for the foundation of ESO.

Magellan's expedition entered the strait at Cabo de las Virgenes on 21 October 1520 and exited via Cabo Deseado on 28 November. The Clouds are mentioned right after they left the strait, in the best-known narrative of the voyage — that by Antonio Pigafetta, who writes:

Il polo antartico non ha stella alcuna della sorte del polo artico, ma si veggon molte stelle congregate insieme, che sono come due nebule [the Clouds]*, un poco separate l'una dall'altra, e un poco oscure nel mezzo. Tra queste ne sono due, non molto grandi né molto lucenti, che poco si muovono: e quelle due sono il polo antartico.* (see Ramusio, 1550).

Obviously neither Pigafetta nor Magellan himself named them the "Magellanic Clouds" — nor indeed did they name the strait after Magellan! The discovery of the passage between the Mar del Oceano (the Atlantic) and the Mar del Sur (the Pacific) quickly became known to sailors and navigators venturing to these remote countries. The race to reach the Spice Islands (the Moluccas) and the competition between Portugal, which controlled the "eastern route" (via the Cape of Good Hope) and Spain which wanted to exploit the "western route" to take possession of new lands, lent great importance to the discovery. Before long this new strait came to be called the "Strait of Magellan" after its discoverer. Of course, the various water channels at the southern end of South America were well known by local fishermen (Alacalufes or Tehuelches), but unfortunately no written reports by locals seem to exist.

As regards the Clouds, history is less clear. Magellan was not the first to reach southern latitudes where the Clouds are visible. On each sea expedition, at least one pilot/astronomer was present to determine the ship's position by astronomical means, so the Clouds could not have escaped their view. However, accounts are few. There are likely two reasons for this. First, the navigators were looking primarily for some star or asterism analogous to Polaris (the North Star) in the south in order to measure the latitude and obviously the Clouds would not serve that purpose. Second, at that time travel documents were kept secret in view of the competition between the various countries. So, to understand the "history" of the Clouds, one needs to follow the history of discoveries and travel in the south, and also the history of the mapping of the southern sky by European explorers and astronomers.

Local populations in South America of course had a knowledge of the southern sky long before Europeans reached that hemisphere. Unfortunately, little is known about their observations as information was transmitted orally and it is only in recent times that efforts have been made to record some of this knowledge before it is lost forever. For instance, the Tupi-Guaranis, in the region of Rio de Janeiro in Brazil, compare the Clouds to fountains (*Hugua*) where a tapir (in the LMC) or a pig (in the SMC) is drinking (Afonso, 2006). Interestingly, the Mapuche in Chile also compare the Clouds to water ponds, called *Rüganko* or *Menoko* in their local language. These water ponds are in the *Wenu Mapu*, the heavens above, and are associated with the *Wenu Leufu*, the river above, i.e., our Milky Way (for example Pozo Menares et al. 2014). The similar nature of the Milky Way and the Clouds was therefore recognised long ago.

Early explorers

Little is known about travel to the south by the Greeks or the Egyptians, although the latter traveled down the Red Sea to seek gold. The first systematic travel in this direction is by the Arabs, progressing along the east coast of Africa or directly to India. When the Portuguese and Spaniards reached India and the Moluccas, they found a lot of trading posts already established by Arabs in India, Indonesia and Malaysia. From there spices were traded, shipped to the Arabic peninsula by boat and then moved further inland. Several nautical sources are available to us, dating back to the Persians or the Arabs. The best known is the *Kitab al-Fawaïd* ("Book of [nautical] principles") of 1475 by the *mu'allim* (master of navigation) Ahmad ibn Majid: this knowledge was so precious that Vasco de Gama enrolled a "*Mu'allim Canaca*" to cross the Indian ocean in 1498. It is clear from those treatises that the Arabs navigated by the stars. They used the Pole Star (*Gah*), and also the big chariot (Ursa Major; *Na's*) or the Pleiades (*at-Turayyä*) and then further down *as-Suhayl* (Canopus) or other southern stars — the stars of the Southern Cross were included in Centaurus; for more details, see Ferrand (1928). But the Clouds, although certainly seen, were of no use for navigation owing to their diffuse nature.

The most ancient record we have of sky observations that include a possible mention of the Clouds seems to be the *Suwar al-Kawakib* (Book of Fixed Stars), written around 964 by the Persian astronomer Abd-al-Rahman al-Sufi. Ludwig Ideler, translating it into German from an extract by Kazvini (Ideler, 1809), includes the following statement:

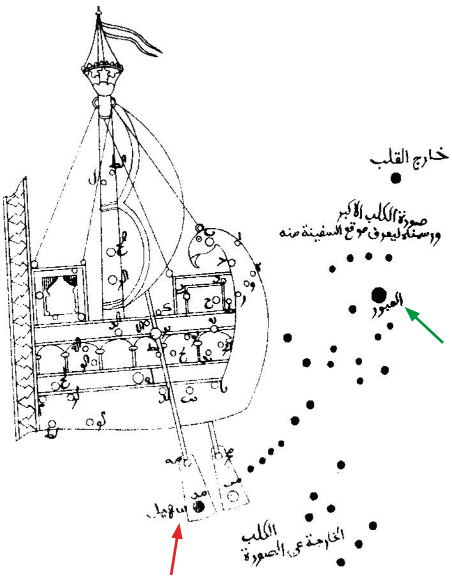

Figure 1. Argo – al Sufi (St. Petersburg manuscript, Schjellerup, 1874). The words at the bottom say "Dog, outside the image". Red arrow: as-Suhayl (Canopus). Green arrow: Sirius (marked "Transient"!).

Unter den Füssen des Suhel (the classical name for Canopus) *steht, wie einige behaupten, ein weisser Fleck, ... den man in Tehama El-bakar, den Ochsen nennt.*

This is believed to be the Large Cloud, which could be seen in good weather conditions from the south of Arabia, although no coordinates were given. In 1874, a translation into French was made by the Danish astronomer Hans Schjellerup directly from an original manuscript; this version is slightly different:

Le vulgaire croit qu'il y a au-dessous des pieds du Suhail quelques étoiles luisantes et blanches qui ne se font voir ni dans Irak ni dans Nadschd, et que les habitants du Tihamat nomment ces étoiles al-bakar, les Vaches.

Schjellerup refers to stars and not a cloud; and *al-bakar* does indeed mean cows or a herd, rather than a bull. The accompanying illustration of the constellation Argo-Navis shows a group of stars, with Suhail (Canopus, indicated by the red arrow in Figure 1) at the southern extremity of the ship's rudder. The illustration on the globe brought back by John Malcolm (Dorn, 1829) shows also a conglomerate of stars south of Canopus rather than a cloud, but the position would be approximately correct.

The Clouds can be seen below about latitude +15 degrees so Chinese voyagers, having long-established contacts with the Arab world, would have seen them when navigating around India. Admiral Zheng He, for example, made seven voyages to Arabia, beginning in 1405. However, these explorations were stopped by the Xuande Emperor (who reigned 1425–1435), and orders were even given to destroy all documents relating to the voyages, so we have no records about their observations today (see Levathes, 1994).

Portuguese sailors were presumably the first western explorers to see the southern sky. While the report of Ca'da Mosto's voyage (1455) mentions only the Southern Cross, the first reference to the Clouds seems to be that by Amerigo Vespucci during his third voyage in 1501–1502:

E fra le altre viddi tre Canopi: i due erano molto chiari, il terzo era fosco e dissimile dalli altri (Mundus Novus, 1504).

The two "clear" clouds and the third "dark and different from the others" are now interpreted as meaning the two Clouds and the Coalsack, although no precise coordinates are given. But a sketch showing southern stars at various times during the night also shows some accompanying nebulosity.

A fleet of 13 Portugese ships, led by Pedro Alvares Cabral and bound for the Moluccas (the "Spice Islands" in Indonesia) to exploit the route opened by Gama, made a significant diversion and reached Brazil (called at that time Tierra de la Vera Cruz) at the latitude of Bahia (~ 14° S) in April 1500. One of the ships was immediately sent back to Portugal to transmit the news of the discovery, carrying with it three letters of report, all dated 1 May. The one by Mestre João (João Faras), physician and navigator, is of most interest to us as it contains a sketch of the southern sky (see Figure 2, left) where the Southern Cross can easily be identified, with the pointers α and β Cen called "guardas", as well as some other stars like the southern triangle. The term "la bosya", in the lower left, is the one used in the north to refer to the small chariot, Ursa Minor, in reference to the Pole Star. This clearly shows that, at least at the beginning, the aim was always to find an asterism able to represent the south pole to aid navigation; this was later abandoned in favour of using the altitude of the Sun to derive latitudes. But there is no mention of the Clouds here (the sketch shows that they would fall at the edge of the map), probably because they are low on the horizon in April–May.

So one had to wait until Andrea Corsali travelled to India and wrote two letters from Kochi (Cochin), in 1515 and 1517, describing his voyage and experiences. The first contains a description of the southern sky (Figure 2, right). The various stars are more difficult to recognise than in Faras's letter, but the Southern Cross is there, and the two Clouds are also

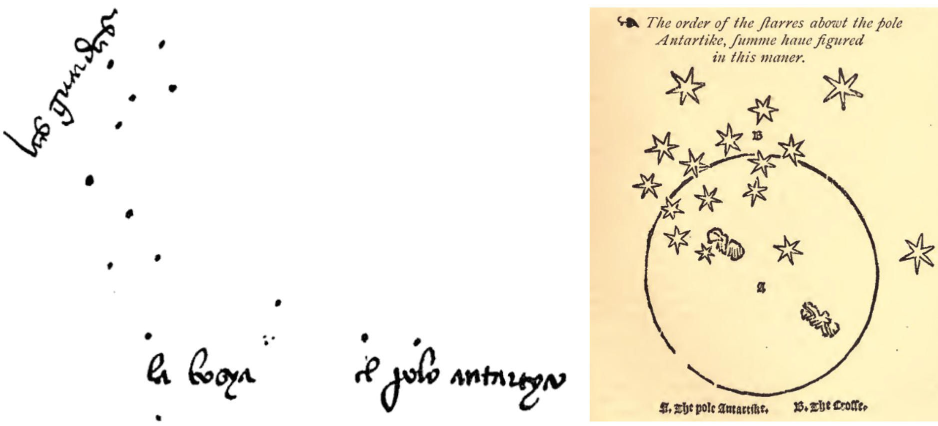

Figure 2. Left: sketch of the southern sky showing Crux (top left) and below it, the Southern Triangle (Mestre Joao, 1500). Right: Sketch from a letter sent by Andrea Corsali in 1515 (translated by Richard Eden).

seen, with a star in the middle which is presumably γ Hyd. He writes:

In che luogo sia il polo antartico, …ed evidentemente lo manifestano due nugolette di ragionevol grandezza (the Clouds)*, ch'intorno ad essa continuamente ora abbassandosi e ora alzandosi in moto circulare camminano, con una stella sempre nel mezzo, la qual con esse si volge lontana dal polo circa undici gradi* (Ramusio, 1550).

This, from 1515, seems to be the first available representation of the Clouds. It is not clear when the mentions of the Cross and the Antarctic Pole were added: Rychard Eden, in his translation of d'Anghiera's *De Orbe Novo* (1555) has this figure with the names — but some earlier manuscripts don't! Several versions of this figure have been published, not always correctly attributed: some even attributed it to Magellan whose travel reports never included any sketch! D'Anghiera in his compilation of travels (d'Anghiera, 1516, in Latin), says *"the Portuguese have gone beyond the fifty-fifth degree of the other pole, where… they could see throughout the heavenly vault certain nebulae, similar to the Milky Way, in which rays of light shone"* (translation by F. McNutt). There is no mention of where he got this from but the description resembles Vespucci's.

Magellan's voyage and his immediate followers

Turning now to Magellan's voyage itself, the details are known largely thanks to the lively reporting of Antonio Pigafetta, "Vicentino Cavagliere di Rodi", who accompanied the expedition to discover the world, and to seek fame (as Pigafetta admits in the introduction to his report). Although the original report, which was written for the Duke of Mantova, has disappeared, several copies or translations quickly appeared, in French, Italian, and Latin.

In an early (shortened) French edition by J. A. Fabre, which is the translation of an original of Pigafetta (circa 1526), one can read, after the passage about the Strait:

Le pôle Antarctique n'est point tant étoilé comme est l'Arctique. Car on y voit plusieurs étoiles petites congrégées (packed) ensemble, qui sont en guise de deux nuées (the two Clouds) *un peu séparées l'une de l'autre, et un peu offusquées* (obscured)*, au milieu desquelles sont deux étoiles non trop grandes ni moult reluisantes et qui petitement se meuvent. Et ces deux étoiles sont le pôle Antarctique.*

In this description, which has no accompanying sketch, it seems that the pole is represented by two small stars in the middle of the two Clouds (possibly γ and ν Hydri), unlike in Corsali's figure. But Pigafetta was not an astronomer, merely a writer who was sensitive to the beauty of the southern sky. His description of the voyage (and hence the Clouds) has probably survived better because it is livelier than the technical reports by navigators. Yet this was not the case in the years immediately following Magellan's discovery of the Strait, when the most printed and distributed document/report was a letter by Maximilianus Transylvanus, secretary to Charles V, first printed in 1523. But it contains no mention of observations, the sky or the Clouds. D'Anghiera mentioned the Clouds in an earlier report (1516), but says nothing about the sky when describing Magellan's trip (d'Anghiera, 1524).

But where are the reports of the navigators and astronomers who accompanied Magellan's expedition? The chief pilot was then Andrès de San Martin, but he was killed, along with more than 20 others, on 1 May 1521 by Humabon, Rajah of Cebu; his papers, which are lost today, nevertheless survived for a while, probably confiscated by the Portuguese in Ternate when the Trinidad returned there. A later report of this voyage by Antonio de Herrera (1601) gives much more detail about the astronomical observations, which must come from San Martin's logbook. I also found a mention of this survival in Bibliotheca Hispana Nova by Nicolas Antonio Hispalensis (1773) and Barros (1553) says that he had "in hand" some papers and a book written by San Martin, collected in the Moluccas by Duarte de Resende. San Martin's observations subsequently percolated into reports by several other authors, and other pilot's reports are also available, but in none of them do we find any mention of the Clouds. Once again, this provides proof that the main interest was initiallyto find stars able to mark the southern celestial pole but not to map the sky, and even this approach was largely abandoned once the solar technique had been mastered[a].

After several expeditions to exploit the discovery of the new route, the fifth trip by Spaniards to the Strait was organised by the Bishop of Plasencia, who sent three ships under Alonso de Camargo, departing in August 1539. After one ship was lost in the Strait, Camargo proceeded in the third ship and went north along the west coast of Chile, becoming the first European to explore this part of the world. He made port at Valparaiso and

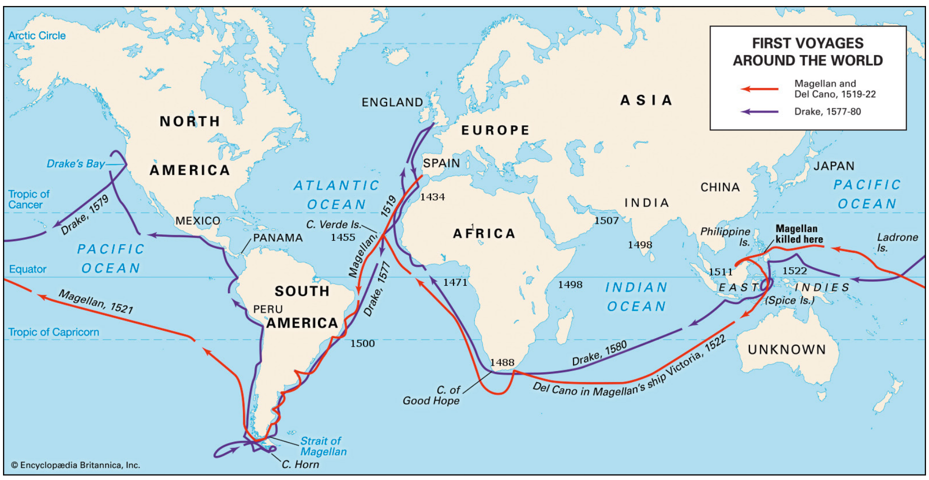

Figure 3. Voyages of Magellan and Drake (from Encyclopedia Britannica), with additional dates of some earlier explorations made by the Portuguese.

proceeded to Peru, where he settled down. Unfortunately no report from that ship remains. The second ship, whose name and captain have not been recorded, went back to Spain after rounding Tierra del Fuego, discovering the southern strait (now called LeMaire). A fragmented report has been discovered by Torres de Mendoza (1879) in which one finds many observations of the Sun to derive latitudes, but nothing about the sky. There is, however, a clear mention of the Strait of Magellan:

A los 12 del dicho (January 1540)*, surgimos junto con el cabo de las Vírgines que está en cincuenta i dos grados largos, y de allí vimos la entrada del Estrecho de Magallanes, é tiene por seña, conviene a saber: el cabo bentallado, etc.*

Later in the text, there are several mentions of the Estrecho (with capital E), showing that only about 20 years after its discovery, Magellan's name was clearly associated by sailors with the strait he had discovered.

A bit later, and unbeknownst to the Spaniards (at least at the beginning), another voyage was undertaken through the Strait and up the western coast of Chile, as far north as San Francisco. Francis Drake's voyage left Plymouth on 15 November 1577 and entered the Strait of Magellan (sic) on 20 August 1578. Again, apart from a lunar eclipse observed on 15 September that year, there is no relevant astronomical observation. I mention this here only because Houzeau (1885) claims that the name Magellan, associated with the Clouds, can be found in Hakluyt (1589), about Drake's voyage of 1578. Besides Hakluyt (1589), all the documents relating to that voyage, including a detailed report by the pilot Nuño da Sylva, can be found in Nuttall (1914) — but I could not find any mention of the Clouds!

It therefore seems clear that by then the name of Magellan was being associated by navigators with the Strait, but not necessarily with the Clouds. This is also indicated by the report of one of the most successful expeditions to the Strait, conducted by the brothers Nodal in 1618–1619, who made the journey in less than 10 months and, remarkably, with no losses. It was said to have been organised to recognise the "*new strait of São Vicente and the one of Magellan*", because "*it had become difficult owing to the number of years during which notice of the navigation had been lost,*" as Sir Clements Markham's translation (Markham, 1911) has it. This report mentions some celestial observations (including the sight of the great Comet of 1618) but there is no mention of the Southern Cross or of the Clouds, as if these were already common knowledge. Clearly, by this point the Sun was the preferred way of determining latitude, together with tables in the Hidrographia Nautica of Cespedes (1606).

Figure 4. The Toucan (Hondius globe, 1600, BNF Paris). Below Tucana is Nubecula Minor; and Nubecula Major is below Dorado, in the lower right corner (arrows).

First mappings of the Southern Sky

The Spaniards' interest in the Spice Islands progressively declined, as they were merely active in getting silver and gold back from Peru and had sold their rights on Moluccas to Portugal. The Dutch launched their first expedition, known as the "*eerste Schipvaart*", under Cornelis de Houtman, who left Holland for the Indies on 2 April 1595. On board were his brother Frederick and Pieter Dirkszoon Keyser (latinised as Petrus Theodori). Keyser had been trained by the cartographer Petrus Plancius, who instructed him to make a record of the southern sky for his celestial globes. This is the first known systematic measurement of the southern sky, probably mostly carried out when the fleet stopped for several months in Madagascar. Unfortunately, Keyser died in Indonesia (reached only in June 1596), but the measurements were probably brought back by Frederick de Houtman in August 1597. During a second voyage with his brother, Frederick complemented those observations further, returning in July 1602. None of Keyser's notes survived, but de Houtman brought back measurements which were long hidden as an appendix to his dictionary and grammar of the Malayan and Malagasy languages (Houtman, 1603), later reprinted as a catalogue of southern circumpolar stars in a French translation by Aristide Marre (1881). They have clearly been used on various celestial globes by Hondius (1598; 1601), Willem Blaeu (1602) and ultimately by Bayer in his Uranometria (1603) where he explicitly mentions Petrus Theodori as the originator of his 12 new constellations (although it is actually Plancius, not Theodori, who is behind these twelve constellations of the southern sky, still in use today with small modifications). Interestingly, no mention of the Clouds is made in Houtman's catalogue but they do appear on Hondius's earlier globes. For instance, of Dorado (where the LMC would be) Houtman (1603) says only: "*Den Dorado heft 4.Sterren,*" and in "*Den Indiaenschen Exster, op Indies Lang ghenaemt*" (our Tucana, close to the SMC), he mentions only six stars. But Bayer's map of the southern pole (his plate 49) indicates both Nubecula Minor and Nubecula Major (without mention of Magellan), Latin being the usual working language at the time.

A detailed analysis of these early mapping attempts can be found in Dekker (1987). Houzeau (1885) claims that Theodori returned in 1597, bringing back "*une énumération des Constellations du Sud en douze astérismes antarctiques...,*" one of which was "*le Nuage*" (the Cloud). Houzeau initially counted 12 new constellations including the Cloud, but then ends up with 21, eight of which were already listed by Ptolemeus: his total now amounted to 13 (21 – 8), including two new ones (Crux and Musca) but excluding the Cloud! While it is clear that Houzeau was misled about Theodori by the comment in Bayer's Uranometria, it is less clear where his idea of the constellation *le Nuage* comes from. Maybe he was influenced by the presentation of the Clouds in the earlier globes of Hondius (see Figure 4) or Blaueu. There are unfortunately many approximate statements in this paper. As for globes, see a detailed description of some of them in van der Krogt (1993) or at the National Maritime Museum in Greenwich, but these are all references to the Nubeculae, not to the name Magellan.

It is clear from these early records that neither the Clouds nor the Southern Cross were of any real interest to the sailors anymore, rather they were merely a curiosity in the sky. The Portuguese, of course, knew them and occasionally mentioned them as the Clouds of the Cape. The development of celestial cartography proceeded and usually included the Clouds, but with their Latin names, Nubecula Minor and Nubecula Major (see, for example, the maps in Bayer's third edition of 1661; or in the atlases of Cellarius, 1660; Pardies, 1675; Flamsteed, 1725; Ottens, 1729). Schiller (1627), in his curious biblical map, includes Tucana, Hydrus and Nubecula Minor in his idiosynchratic constellation of St Raphaël. In his Uranographia, where the names of 30 Dor or 47 Tuc come from, Bode (1801) uses both German and French, but does not mention Magellan.

Two major efforts to get better celestial cartography in the south were undertaken after Plancius. The first was by Edmond Halley from the island of St Helena, where he had been sent by John Flamsteed the first English Astronomer Royal; he observed during 1677 and published the Catalogus Stellarum Australium (Halley, 1679). His work is known because of the inclusion of a new (fleeting) constellation, Robur Carolinum, to please King Charles II. He mentions in an appendix that:

Proxima, ex iis quas observavi, est in Cauda Apodis, in distancia paulo ultra 8 graduum, Duae Nubeculae, quae a Nautis Nebulae Magellanicae appellantur, exacte referent Galaxiae albedinem & Telescopio inspectae, hinc inde Nebulas Parvas & exiguas Stellas ostendunt...

It appears it was clear to him that the name Magellanic Clouds was used only by sailors, and that those Clouds resemble the Milky Way. The only other mention in the catalogue itself comes in the final list of bright stars "*in Usum Navigantium*", useful for navigation, where the first in the list is "*quae adjacent Nubeculae minori*", close to the Small Cloud. The Clouds also appear as Nubeculae in his Planisphère of 1678.

The second effort was by Nicolas de La Caille who observed at the Cape of Good Hope between August 1751 and July 1752. He published a catalogue of southern nebulae (or, more precisely, of nebulous stars) in 1755, in which the Clouds are not listed, probably because they were too large for his purpose (47 Tuc and 30 Dor are mentioned). In the introduction he says that he observed the brightest regions of the Milky Way several times with a 14-foot (4.25-m) focal length telescope, and compared them to the two Clouds:

"qu'on appelle communément les <u>nuées de Magellan</u> et que les Hollandais et les Danois appelent les <u>nuées du Cap</u> (his underlining)*. On voit évidemment que ces parties blanches du ciel se ressemblent si parfaitement, qu'on peut croire, sans trop donner aux conjectures, qu'elles sont de même nature,..."*

He adds that these Clouds seem to be detached parts of the Milky Way, and that it is not clear that their whiteness would be caused, as is usually believed (sic), by clusters of small stars more tied together than in other parts of the sky, as he could not resolve them with his telescope. About the names, he also says:

D'ailleurs, la plupart des Navigateurs appellent nuages du Cap, ce que nous appelons nuées de Magellan, ou le grand & le petit nuage.

In the celestial map completing his publication (see Figure 5) the two Clouds do indeed appear under the names "*le Petit, et le Grand Nuage*". But his words, "*que nous appelons nuées de Magellan*", seem to indicate that around that time the association of the Clouds with Magellan was already spreading beyond the nautical community, even if the scientific term was still simply Nubeculae or les Nuages.

When James Dunlop described his observations of the southern sky (Dunlop, 1828) "*made at my house*" in Paramatta, near the Brisbane Observatory in Australia, he reported that he made: "*very correct drawings of the Nebulae major and minor... with an excellent 9-feet reflecting telescope*" but there is not a single mention of Magellan. He gives detailed sketches of both nebulae, with the positions of many stars and smaller nebulae within.

When Rümker later published his catalogue (Rümker, 1832) based on observations from the Observatory of Paramatta, Australia, he states that "*the Nubeculae major and minor of LaCaille are two fragments of the via lactea and distinguish themselves by nothing from any other parts of it requiring, with the exception of two nebulae, no powerfull telescope to be dissolved in well-defined Star's*" — again, no mention of Magellan.

John Herschel (1847), in a section entitled "On the two nubeculae or Magellanic Clouds", talks only about Nubeculae. Only in the accompanying figure, where he gives his visual observations, does he mention, "*The two Magellanic Clouds as seen with the naked Eye*". So he uses both the scientific denomination and the more public name, and Herschel seems to have been the first to use the name Magellanic Clouds in scientific publications. Later, in the first edition (1910) of the well-known Norton's Star Atlas, it is stated that, "the Magellanic Clouds or Nubecula Major and Nubecula Minor appear to the naked eye like detached portions of the Milky Way, and are a marvelous sight in the telescope" as if their names were obvious, but without any further note on Magellan (nor on their nature). So, although no precise date can be given, it seems that by the late 19th century, the term Nubecula was still being used in scientific exchanges, but the term Magellanic Clouds was progressively passing from nautical circles to the public and scientific spheres, finally replacing Nubeculae once scientists abandoned Latin.

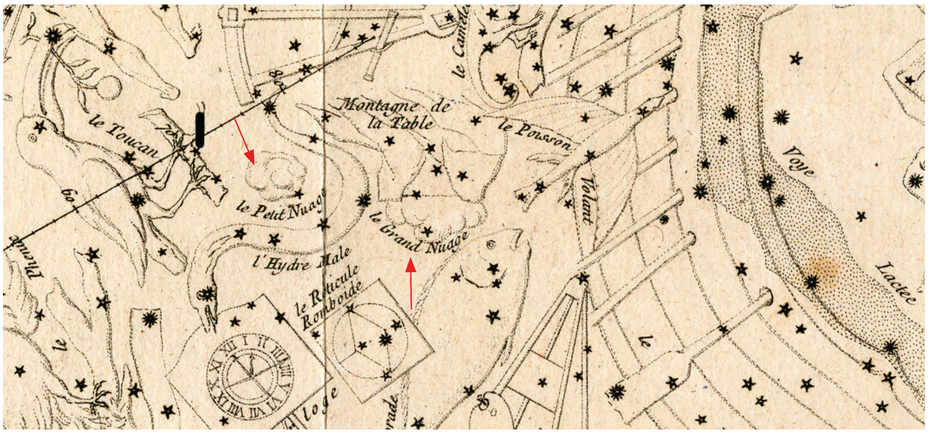

Figure 5. Enlargement of La Caille's map of 1752, showing the two Clouds (red arrows; Paris Observatory).

To conclude about Magellan, one may turn to words from the introduction to Drake's famous voyage (Ed. 1628):

Fame and envie are both needlesse to the dead because unknown, sometimes dangerous to the living when too well knowne: reason enough that I rather chuse to say nothing, then too little, in the praise of the deceased Author.

It is more difficult now to observe "at my house", as Dunlop did, but astronomers travelling to Chile should keep in mind how hard it was to reach that country in those early days. Today, we do it in 14 hours, instead of 14 months.

Acknowledgements

A longer version of this article is available at arxiv:2009.04973. Many of the texts have not reached us in their original language, but rather in Latin, French (or, later, English) translations. Whenever possible, I have presented text in the original language (except Arabic), to also reflect the diversity of languages in use in the ESO community. Concerning travel and the discovery of the southern hemisphere, some of the compilations mentioned above — to which the reader may refer for more details — such as de Barros (1552), d'Anghiera/Eden (1516/1555), Ramusio (1550), Herrera (1601) or Fernández de Navarrete (1837), are available online; some travel reports have been translated into English by the Hakluyt Society (which honours the work of Richard Hakluyt himself [1553–1616]). Regarding Magellan's journey, most available documents have been assembled in the excellent, recent book by de Castro (2010). Many detailed reports of Portuguese travels (by da Mosto, Vespucci, Gama, etc.) have also been published by Éditions Chandeigne (Paris).

This work is of course not the first dealing with the discovery and description of the southern sky. While conducted independently, it has also benefited, in addition to the references and compilations quoted above, from prestigious predecessors. To mention at least the most important ones: the Kosmos from Alexander von Humboldt, the 3rd volume of which appeared in 1851; the report by E. Halley, which appeared in 1679 in Latin in London, and the same year in Paris translated into French; and the reports of La Caille, which appeared in Paris in the Mémoires de l'Académie des Sciences in 1752 (p. 586) and 1755 (p. 194). See also the IAUS 190 in 1998 where Paul Hodge dealt with that topic (1999, IAUS190, ed. Chu, Y. H. et al., (ASP), 3).

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Notes

[a] The oldest surviving manual for navigation, the Portuguese *Regimento do Estrolabio*, which probably dates from 1509, sits not in Evora, but in Munich (ex Royal Library), see *Seltenheiten aus Süddeutschen Bibliotheken* (Freys, E. 1912, (München), and Bensaúde, J. 1912).

[b] d'Anghiera, P. M., *De rebus oceanis et Orbe Novo Decades* has been reprinted and translated many times, including *The Decades of the Newe Worlde or West India*, translated into Englysshe by R. Eden (1555, London: Rychard Iug), a French translation by P. Gaffarel (1907, Paris), and an English translation by F. MacNutt (1912, London).

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Report on the ESO Workshop

A Synoptic View of the Magellanic Clouds: VMC, Gaia, and Beyond

held at ESO Headquarters, Garching, Germany, 9–13 September 2019

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The year 2019 marked the quincentenary of the arrival in the southern hemisphere of Ferdinand Magellan, the namesake of the Magellanic Clouds, our nearest example of dwarf galaxies in the early stages of a minor merging event. These galaxies have been firmly established as laboratories for the study of variable stars, stellar evolution, and galaxy interaction, as well as being anchors for the extragalactic distance scale. The goal of this conference was to provide fertile ground for shaping future research related to the Magellanic Clouds by combining state-of-the-art results based on advanced observational programmes with discussions of the highly multiplexed wide-field spectroscopic surveys that will come online in the 2020s.

Motivations

Observational access to the Magellanic Clouds system was one of the key scientific drivers to build large telescopes in the southern hemisphere, which led to the foundation of ESO itself. Almost 60 years later, the Magellanic Clouds are still very much at the centre of the discourse, providing fundamental insight into several hot research topics. The Magellanic Clouds are our nearest examples of dwarf galaxies at an early stage of a minor merger event. The distribution of their stars and gas provides evidence of an active history of formation and interaction. Thanks to wide and deep photometric observations obtained during the last decade, we have been able to describe the star formation history and the geometry of the Magellanic Clouds at an unprecedented level of detail. The VISTA near-infrared ESO Public Survey of the Magellanic Clouds system (VMC) has played a major role in this endeavour.

In this workshop, the most interesting discoveries emerging from the VMC and other contemporary multi-wavelength surveys were discussed. These results have cemented stellar populations as important diagnostics of galaxy properties. Cepheid stars have, for example, revealed the three-dimensional structure of the system, giant stars have shown significantly extended populations, and blue horizontal branch stars have indicated protuberances and possible streams in the outskirts of the galaxies. The complementary view provided by RR Lyrae stars shows instead regular and ellipsoidal systems. The analysis of the star formation history suggests that the Small Magellanic Cloud (SMC) formed half of its mass prior to about 6 Gyr ago, while a proper motion map reveals tidal features, for example, behind the main body of the galaxy and along the line of sight. The Magellanic Clouds may have arrived at the Milky Way system only recently, together with associated satellite galaxies, and may be more massive than we used to think. The chemical information that was derived, albeit for limited types and numbers of stars, is highly valuable for understanding the internal structure of the galaxies as well as the geometry and chemical evolution of the system — for example, the origin of the Magellanic Stream. For the first time, astronomers are beginning to link age and metallicity distributions with the kinematics and structure of stellar populations, thereby deciphering the formation and evolution of the Magellanic Clouds in great detail.

Within the next year, important observing programmes targeting the Magellanic Clouds will reach completion and provide unique datasets through which the study of the stellar populations will unfold. Moreover, the imminent release of new Gaia data is expected to shed new light on the precision to which stellar populations parameters can be characterised. The Magellanic Clouds remain a unique astrophysical laboratory, for investigations of stellar evolution, star clusters, the distance scale and the measurement of the local value of the Hubble constant to high precision. Future developments focus on using wide-field, high-multiplex spectrographs and powerful images to obtain a robust chemical understanding of the system and use stellar population diagnostics across the Hertzsprung-Russell diagram with unprecedented precision. Most of these developments will culminate in the early 2020s and discussions on how to formulate the most relevant scientific questions are already advanced.

Summaries of talks and highlights from sessions

The workshop revolved around eight scientific sessions at which a total of 64 talks were presented and a summary is given below. There were also 28 posters complementing each session. A vote was held to select the best among them and the winner was the poster by Raphael Oliveira on "Age and metallicity gradients in the Magellanic Bridge with the VISCACHA survey", which received a prize — a framed photograph of the 30 Doradus press-release image that was produced by the VMC survey.

The Magellanic Clouds in context

Joss Bland-Hawthorn opened the meeting by highlighting the importance of the Magellanic Clouds as galaxies that have contributed to the growth of the Milky Way. Recent results on the gas distribution, the internal motions of stars and their chemical composition reinforce the Clouds as a place to study many astrophysical processes under different environmental conditions. The orbital history of the Magellanic Clouds, which is reflected in their star formation history, can be used to establish the influence of the Milky Way and to probe the physics of the dark matter halo. Subsequently, Laura Sales reminded us that Lambda-Cold-Dark-Matter (ΛCDM) substructures around dwarf galaxies indicate that the Large Magellanic Cloud (LMC) must have brought along several of its own dwarf satellites. She argued that, as a result of their recent infall, the dark and baryonic matter would follow a specific path on the sky. Indeed, the combination of deep photometry and accurate astrometry from Gaia has revelaed that several ultra-faint dwarfs, together with some low-mass classical dwarfs, are consistent with having been accreted as part of the

LMC group. This also implies a large LMC virial mass at infall ($M_{200} \geq 3 \times 10^{11}\ M_\odot$) and a direct influence of the LMC on the star formation history of its satellites. Elena Sacchi concluded that the star formation history of ultra-faint dwarfs associated with the Magellanic Clouds differs from that of similar objects associated with the Milky Way.

Satellites that are likely members of the Magellanic Clouds are characterised by bright horizontal branches, dispersed red giant branches and a star formation history that stopped 1–2 Gyr earlier than in ultra-dwarf systems of the Milky Way. Ethan Jahn illustrated, using zoom-in cosmological simulations to study LMC-mass analogues, that tidal interactions with the central galaxy allow the retention of more substructure than in Milky Way-mass hosts, but similarly cause tidal stripping of satellites, suggesting that future kinematical studies will reveal additional satellites associated with the Clouds.

Alice Minelli addressed both the LMC and the Sagittarius dwarf galaxy, the latter being in a more advanced stage of gravitational interaction with the Milky Way than the LMC is. A high-resolution spectroscopic study of 25–30 red giant branch stars per galaxy, measuring the abundance of alpha-, light-, Fe-peak and neutron-capture elements, showed that the two dwarfs experienced a very similar chemical enrichment history despite their current differences, i.e., the LMC still contains gas and presents ongoing star formation while the Sagittarius dwarf is predominantly an old system deprived of gas. Marcel Pawlowski’s review dealt with the plane of satellite galaxies problem. Satellite galaxies of the Local Group arrange themselves in narrow structures, with the Magellanic Clouds associated with the Vast Polar Structure, and the Magellanic Stream curiously aligned with other structures, with signs of kinematic correlation (supported by Gaia proper motions) indicative of corotation. Planes of satellites are not common in ΛCDM simulations and their potential origins include the following: accretions from preferred directions (filaments), group infall or a tidal nature of the dwarf galaxies — there are elements both in favour and against such possibilities.

Evolution of stars and star clusters in the Magellanic Clouds

The meeting continued with a rich session devoted to the evolution of stars and star clusters, since the Magellanic Clouds provide, in this context, the best samples at sub-solar metallicities. Leo Girardi discussed the calibration of overshooting in main-sequence stars and the evolution of asymptotic giant branch stars, which are critical to determining the nuclear fuel burnt by blue and red stars, and model spectra of 0.1–5 Gyr-old distant galaxies. This work is usually performed in respect of stars that are members of star clusters, where stellar rotation plays a significant role. Field stars, however, where the star formation history is derived, represent a promising input to the calibration of asymptotic giant branch models that also take pulsation and mass-loss into account.

The phenomenon of multiple populations, observed in star clusters of different ages, was reviewed by Nate Bastian. The split main sequence in young (< 1 Gyr old) clusters and the extended main-sequence turnoff in clusters < 2 Gyr old can both be explained using rotation as the dominant mechanism; the large fraction of rapidly rotating stars is supported by a large (~ 60%) fraction of Be stars in these clusters. Seth Gossage demonstrated that stellar evolutionary models that include stellar rotation are able to account for the majority of extendend main-sequence turnoff morphologies. However, other effects like age spreads and braking are not ruled out. Andrea Dupree showed that important constraints to the models of these effects are obtained from high-resolution spectroscopic observations of Hα and He I. Furthermore, Ivan Cabrera-Ziri confirmed that neither massive stars nor low-mass stars in young clusters show element abundance variations. On the contrary, a spread in light element abundances (for example, N, Na, C, O, Mg, Al) is likely responsible for the split red giant branches in older clusters. Silvia Martocchia showed the results of a study of about 20 massive ($> 10^4\ M_\odot$) star clusters in the Magellanic Clouds where, for the first time, multiple populations were found in clusters as young as 2 Gyr. A larger abundance spread was found in older clusters compared to younger ones, while age differences within a given cluster are < 20 Myr. Complicating the picture, Paul Goudfrooij showed that the faint main sequence of young LMC star cluters is characterised by a kink which is not reproduced by stellar isochrones. This is probably associated with a sudden decrease of temperature resulting from an expansion of the convective envelope in stars with masses $< 1.45\ M_\odot$, at the metallicity of the LMC, which may cause braking. Interestingly, the main sequence below the kink of several clusters is consistent with that of a single stellar population.

The properties of the high-mass populations of the Clouds were reviewed by Chris Evans who emphasised the results obtained from the VLT-FLAMES Tarantula Survey. In particular, it was shown that the percentage of binary stars is similar to that in the Galaxy, that it extends to B stars and that there is an excess of massive stars in the region of 30 Doradus with respect to predictions based on the initial mass function. Future observational projects will target SMC massive stars in the ultraviolet to support models at low metallicity. Joachim Bestenlehner focused on the star cluster R136 at the core of 30 Doradus. The cluster age peaks at 1.2 Myr and its most massive stars ($M > 100\ M_\odot$) account for a quarter of the ionising flux and 2/3 of the mechanical feedback. A comprehensive catalogue of 1405 red, 217 yellow and 1369 blue supergiant stars across the SMC was presented by Ming Yang. It stemmed from multi-wavelength observations, from ultraviolet to far-infrared with 29 different filters, and the combination with Gaia data to identify SMC members down to a minimum mass of 6–7 $M_\odot$. Among the intermediate-mass (3–10 $M_\odot$) red supergiants are also Cepheids for which ages strongly depend on model physics — for example, including stellar rotation makes the stars older. Richard Anderson argued that new tests confronting dynamical and evolutionary timescales for Cepheid members of star clusters are needed.

Star formation history and chemistry across the Magellanic system

Andrew Cole opened the third section of the meeting with a review of the star formation history of the Magellanic Clouds. He highlighted that these nearby galaxies could be both a blessing and a curse, in that they provide an extremely rich population of stars across a Hubble time on the one hand, and on the other hand a level of detail over a large area of sky such that, "no single field is ever going to be totally representative". The LMC had a strong initial phase of star formation that then declined, picking up again 3–5 Gyr ago, while the SMC started forming stars vigorously only 5 Gyr ago.

Star formation histories derived from deep photometry were presented by Tomás Ruiz-Lara from the application of a well-established colour-magnitude diagram fitting technique. Additonal episodes of star formation were identified, as well as differences in the building up of particular regions. The extremes of the LMC bar appear younger and more metal rich than the disc which appears metal poor, but older in the south than in the north. Alessio Mucciarelli reviewed the chemical information obtained from spectroscopic investigations at low resolution (based on the CaII triplet method for a general assessment of the overall metallicity) and at high resolution (based on the abundance of other elements such as Ba and Eu).

Different studies agree on the lower [α/Fe] abundance in the LMC compared to that in the Milky Way, which also indicates a lower star formation rate. However, there is disagreement on the slope of [α/Fe] as a function of [Fe/H] and on the position of the [α/Fe] knee, marking the onset of the influence of type Ia supernovae. Mathieu Van der Swaelmen presented the analysis of FLAMES spectra of red giant branch stars in a few LMC fields. He found that [Mg, O/Fe] are indeed lower in the LMC than in the Milky Way, while [Si, Ca, Ti/Fe] are similar. This suggests that the chemical history of the LMC was dominated by type Ia supernovae and intermediate-mass type II supernovae, without significant differences among the three fields.

Large-scale infrared surveys have allowed the identification of galaxy-wide samples of young stars, as explained in Joana Oliveira's presentation. This is a crucial step in studying environmental dependencies on star formation and early stellar evolution in order to understand the role of metallicity and galactic structure. In particular, LMC young stellar objects show high accretion rates and significant light-curve variations, while the distributions of upper- and pre-main sequence stars support hierarchical and dust heating substructures. Clifton Johnson showed the powerful impact of the combination of observations with the Atacama Large Millimeter/submillimeter Array (ALMA) and the Hubble Space Telescope (HST) on studies of pre-main sequence stars and their environment in the Magellanic Clouds. The star formation efficiency of molecular clouds in the SMC (~ 2% with 0.5 dex spread) appears consistent with that in the Milky Way and shows a correlation with cloud age.

Gas and dust within the Magellanic system

Naomi McClure-Griffiths presented an overview of the atomic gas in the Magellanic system, including the Magellanic Bridge, Stream and Leading Arm, which are predominantly gaseous features. A spectacular map of the SMC, with a spatial resolution 10 times higher than that of previous maps, shows a cold (T < 400 K) gas outflow (35–60 km s^{-1}), about 40% of which is beyond escape velocity. This implies an HI mass flux of 0.2–1 $M_{\odot}$ yr^{-1}, 2–10 times larger than the rate of star formation in the SMC, which is therefore likely to quench in 0.2–3 Gyr. The rotation curve resembles that of a rotating disc. Both cold and ionised gas (for example, Si I, Si II, Hα) reside in both the Stream and the Leading Arm. Andrew Fox highlighted the dual chemical origin of the Stream, from both the LMC and the SMC, whilst abundances in the Leading Arm suggest an SMC origin; their variation corroborates a scenario in which the different clumps represent shredded dwarfs accreted as part of the Magellanic group. The average temperature of HI clouds is 30 K and there seems to be a clear correspondence between the location of these clouds and that of the small clumps of CO emission and/or molecular gas, as revelaed by ALMA observations and presented by Katie Jameson. Kat Barger provided an overview of the significant amount of ionising debris surrounding the Magellanic Clouds as revealed by the highest sensitivity emission-line Wisconsin Hα Mapper (WHAM) survey. She also showed that supernova explosions in the LMC sustain a large-scale emerging wind (0.4 $M_{\odot}$ yr^{-1}). The level of ionisation in the Stream cannot be explained simply by photoionisation.

The dust content and stellar feedback of the Magellanic Clouds were discussed by Margaret Meixner with a particular focus on the results obtained from projects based on infrared observations with the Spitzer and Herschel space telescopes. The LMC and SMC contain 7.3 x 10^5 $M_{\odot}$ and 8.3 × 10^4 $M_{\odot}$ of dust, respectively, accounted for by asymptotic giant branch stars, red supergiants and supernova production, as well as by dust growth by accretion. The LMC dust is predominantly made of amorphous silicates, while both amorphous silicates and carbon are

Figure 1. Conference photo.

present in equal amounts in the SMC. Future space missions like the James Webb Space Telescope will allow us to determine the compositon of the dust in the ejecta of supernova 1987A.

Sikia Gautam studied the correlation between far-ultraviolet (associated with dust) and mid-infrared (associated with polycyclic aromatic hydrocarbon molecules) intensities in many diffuse locations in the SMC, concluding that ultraviolet emission originates in the interstellar field rather than in the intervening medium along the line of sight. Pierre Maggi showed that dust is destroyed as a result of supernova explosions at a rate that depends on the specific element: it is higher for O and Fe and lower for Mg and Si. X-ray survey results also show that the higher numbers of core-collapse supernovae compared to type I in the SMC, compared to the LMC, are perhaps related to their star formation history. Furthermore, supernovae in the LMC appear located in front of the disc (projected onto the bar) or behind it (belonging to 30 Doradus). By studying the spectral energy distribution of background galaxies (from *u* to *K* bands and with redshift < 6), Cameron Bell mapped the total instrinsic reddening of the SMC. This method successfully recovers high values in the centre and low values in the external regions utilising galaxies with low levels of intrinsic reddening.

Internal kinematics and dynamics of the Magellanic Clouds

Denis Erkal demonstrated that the mass of the LMC is large, ~ 10^{11} $M_{\odot}$, and because of that it must have influenced tracers of the Milky Way structure. In particular, a better sky track, distance, proper motion and radial velocity for members of the Orphan stream are obtained when the LMC mass is taken into account. In addition, velocity shifts of Milky Way satellites, warps of the Milky Way disc and a pull of the Milky Way mass internal to 30 kpc can be explained by an LMC influence. Gurtina Belsa argued that only a massive LMC on first infall can maintain the SMC as a binary companion and survive a stable disc after a recent (< 200 Myr) and direct (< 10 kpc) collision. This event is probably responsible for the formation of the one spiral arm and the offset of the disc from the bar in the LMC. At least 30% of Milky Way-type galaxies host an LMC-mass galaxy, with 70% having accreted at least one. Dwarf pairs around these hosts are however rare — they occur in only 6% of cases.

Dana Casetti-Dinescu examined the elemental abundance and three-dimensional kinematics of OB-type stars in the periphery of the LMC, where she confirmed that some stars were born in situ. While the origin of similar stars in the Leading Arm is not clear, they could have formed (and may still be forming) in the LMC disc or in the Milky Way. Lara Cullinane explored the kinematics of the periphery of the LMC using data from the Magellanic Edges Survey (MagES) combined with Gaia. A feature in the northern disc of the LMC shows different kinematics from that of the disc, as obtained from a variety of disc rotation models. Scott Lucchini used hydrodynamical simulations in a tidal scenario to reproduce the Stream and Leading Arm gas.

It is, however, difficult to account for the gas mass in the Stream and the fragmentation of the Leading Arm at the same time. Preliminary simulations including the influence of the Milky Way hot corona show a diffused Leading Arm made predominantly of LMC material and some fragmentation in the trailing arm while matching the observations of the two LMC and SMC filaments. Yang Yanbin showed instead that a hydrodynamical simulation in a ram-pressure-plus-collision scenario is able to reproduce many properties of the Magellanic system, such as the density of HI and the mass of ionised gas in the Stream with a 20% accuracy, the leading arms, and the three-dimensional structure of young and old stars. Florian Niederhofer used data from the VMC survey to calculate the proper motion of young and old stars across the SMC. The median SMC motion and the velocity pattern across tiles are consistent with literature determinations for both samples. Andres del Pino used Gaia data and a neural network method trained on the line-of-sight velocity of young, < 1 Gyr old, stars and on the distance of old RR Lyrae stars, and applied this to > 6 million stars with six-dimensional information, including age and metallicity, to study the distribution and kinematics of stellar populations within the Magellanic Clouds. Their results reproduce two bridges (young and old) separated in distance by about 1.5 kpc, connecting extended distributions characterised by different kinematics.

The Magellanic Clouds as a distance scale anchor

Grzegorz Pietrzynski led us through the necessary steps to determine an accurate distance to the LMC using eclipsing binaries, one of the primary distance indicators in nearby galaxies, addressing the major sources of error in the calibration of the distance scale (population, extinction, zero-point, blending and physics of the indicator). Many years of extensive photometric and spectroscopic observations were invested to reach an accuracy of 1%.

The role of the LMC in the distance scale was further discussed by Lucas Macri with respect to results on Cepheids and Mira stars, among the secondary distance indicators. In particular, the combination of sparse near-infrared observations and highly sampled optical light curves, as well as single observations with the HST to overcome crowding, provides a significant improvement to the period-luminosity relations used to derive distances, effectively reducing the uncertainty in the Hubble costant. Furthermore, a new periodogram technique based on a multi-band model to fit the light curves will allow us to recover the period of many Mira stars beyond the LMC, to be detected in the future by the Synoptic Survey Telescope at Rubin Observatory. Anupam Bhardwaj showed that period-luminosity relations for Mira stars at maximum light have a 30% less dispersion than at mean light. This is likely due to the destruction of unstable molecules when the Mira is at its warmest phase. Marek Gorski focused on the tip of red giant branch method to derive distances of systems at ~ 2 Mpc from ground-based and ~ 16 Mpc from space-based observations. He highlighted recent improvements to the reddening, edge-detection method and to the near-infrared absolute magnitude calibration.

The most accurate period-luminosity relations for Cepheids in the LMC and SMC, based on near-infrared photometry from the VMC survey, were presented by Vincenzo Ripepi. However, the calibration of these relations, which is based on Cepheids in the Milky Way and the current Gaia data, is still influenced by a metallicity effect and parallax uncertainties. These issues will most likely be fixed in subsequent releases of the Gaia data. To quantify the influence of metallicity on the Cepheid period-luminosity relations, Wolfgang Gieren showed an application of the infrared surface brightness technique to Milky Way, LMC and SMC sources. While the slopes of the relations are not influenced by metallicity, the zero-points are — in the sense that more metal-poor Cepheids are fainter by –0.23 +/– 0.06 mag/dex. Bogumił Pilecki explained that Cepheids in eclipsing binary systems allow us to derive physical parameters (for example, period, mass, and radius) from which to obtain evolution and pulsation models. These results place important constraints on, for example, the projection factor (the ratio between the pulsation velocity of the star and its radial motion), a crucial quantity for the calibration of the infrared surface brightness technique. Roberto Molinaro showed the results of fitting non-linear convective pulsation models to the light and radial velocity curves of a sample of Cepheids in both the LMC and the SMC. Extensive grids of models are built for each individual star to derive structural parameters, distance and reddening, as well as to contruct period-luminosity and period-mass relations for comparison with those derived from observations.

Morphology and structure of the Magellanic Clouds from different stellar populations

Smitha Subramanian analysed data from the VMC survey and showed evidence for a population of red clump stars ~ 12 kpc in front of the SMC, emerging from a region ~ 2.5 kpc away from the centre and towards the east. This population was probably stripped during the last interaction episode with the LMC 300–400 Myr ago. Michele Cignoni presented data from the STEP (SMC in Time: Evolution of a Prototype interacting late-type galaxy) survey, where a bimodal red clump is also detected and where the bright component dominates the Magellanic Bridge. Furthermore, an analysis of blue-loop (core He burning) stars showed that star formation moved from the northeast of the SMC to the southwest; the age ranges in these regions span 120–200 Myr to 120–60 Myr, respectively, while both ranges are present in the central regions.

Dalal El Youssoufi used the VMC survey data to explore the morphology of the Magellanic Clouds, creating maps with a spatial resolution of 0.13–0.16 kpc at different ages. These maps demonstrate in great detail the history of interaction and evolution of the Magellanic Clouds. Anna Jacyszyn-Dobrzeniecka analysed data from the OGLE-IV survey to characterise the three-dimensional structure of the Magellanic Clouds. The clumpy appearance traced by Cepheids contrasts with the regular distribution traced by RR Lyrae stars in both galaxies. The spatial extension of old stars supports the presence of two halos rather than a bridge connecting the LMC with the SMC. Massimiliano Gatto searched for stellar clusters in the outskirts of the LMC using deep photometric data obtained at the VLT Survey Telescope, from the YMCA (Yes, Magellanic Clouds Again) survey, and found 55 new candidates. Most of these clusters are of intermediate age (1–4 Gyr old) with a peak at 2 Gyr and only a few clusters in the age gap (4–10 Gyr).

Doug Geisler showed that the metallicity distribution of stellar clusters in the SMC is bimodal, with peaks at about [Fe/H] = –0.8 and –1.1 dex, and does not show evidence of a strong gradient, while field red giant branch stars have a unimodal distribution (peaked at [Fe/H] = –1.0 dex) and a negative gradient that reverses to positive beyond 4 degrees from the centre of the galaxy. The age-metallicity relation of the clusters shows a significant dispersion at all ages. In the presentation by Noelia Noël, supporting evidence was given for the disruption of the SMC: the gas appears decoupled from the stars, the kinematics of giant stars shows a lot of debris around a bound core and there are breaks in the low surface-brightness profile of young stars. It is also likely that the total mass of the SMC was much larger than the accepted value. Pushing to low surface brightnesses, Vasily Belokurov reviewed the recent studies of the detection of ultra-faint satellites and their association with the Magellanic system; currently 7% of the Milky Way satellites could be brought in by the LMC.

Satellites might also have been destroyed in the LMC group environment and this process most likely created stellar streams. In the LMC the southern arm appears as the counterpart of the northern arm, while there are many other tentacles that are possibly associated with episodes of earlier interactions between the Clouds. Further insight into the periphery of the Magellanic Clouds was given by Gary da Costa (on behalf of Dougal Mackey). Numerous structural distortions were found within the area covered by the MagES survey (~ 1200 square degrees around the LMC and ~ 200 square degrees around the SMC). The offset of several degrees between intermediate-age and old stars in the SMC might be related to an LMC-SMC encounter > 2 Gyr ago.

Young stars in the Bridge form a chain of diffuse clusters in line with HI observations, supporting a feedback process from supernovae and stellar winds. Camila Navarrete confirmed, using spectroscopic observations of individual stars, that two of the streams previously detected from the distribution of blue horizontal branch stars are indeed kinematically coherent structures. On the other hand, the Pisces overdensity is difficult to associate with Magellanic debris, but may be consistent with the expected Magellanic wake into the Galactic halo. The discovery of a young cluster, associated with the Leading Arm because of its distance, metallicity and radial velocity, was presented by Adrian Price-Whelan. This cluster was found from a search of co-moving blue horizontal branch stars and subsequent follow-up studies; it might have formed as a result of the interaction between the Leading Arm and the Milky Way gas.

Ongoing and future surveys of the Magellanic Clouds

David Niedever opened the last session by presenting results from two surveys: the Survey of the Magellanic Stellar History (SMASH) and the Magellanic Clouds survey using the Apache Point Observatory Galactic Evolution Experiment (APOGEE).

Their combination will set constraints on the evolution of the galaxies. In particular, deep photometry was used to derive a three-dimensional map of the LMC, to detect a warp and a stellar ring in its disc, and to probe the stellar periphery to 21 degrees from the centre. Extensive spectroscopy was used to derive the (low) star formation efficiency compared to that of the Milky Way — supporting their formation in low-density environments and a first infall scenario. Bruno Dias introduced the VIsible Soar photometry of star Clusters in tApii and Coxi HuguA (VISCACHA) survey aimed at the study of stellar clusters in the Magellanic Clouds. The spatial resolution of this survey is better than that achieved by other ground-based photometric surveys because of the use of adaptive optics, which should improve the derivation of the physical properties of stellar clusters (age, mass, reddening, distance, and structural parameters) from the interpretation of colour-magnitude diagrams.

Maria-Rosa Cioni focused on two surveys using the VISTA telescope: the recently completed near-infrared photometric survey VMC and the planned spectroscopic 1001MC (One Thousand and One Magellanic fields) survey. Highlights from the VMC include: the spatial variation of the distribution of mass in the SMC, developing an elongated shape between 5 and 3 Gyr ago, truncated to the west between 500 and 200 Myr ago; the dominant number of 100 Myr-old Cepheids in the northwest of the SMC at closer distances compared to the majority of 200 Myr-old ones in the centre; and the significant distance modulus variation across the LMC and SMC obtained from the tip of the red giant branch method. The scientific goals, area, type and number of targets (about 0.5 million stars and 0.1 million background galaxies) that the 1001MC plans to observe, as part of the consortium that develops the 4-metre Multi-Object Spectroscopic Telescope (4MOST), were also presented. First results from the Galactic ASKAP (Australian Square Kilometer Array Pathfinder) survey, including the Magellanic Clouds and Bridge, were shown by Nickolas Pingel. In particular, he reported the first detection of a break in the power spectrum of HI, demonstrating that this high spatial and spectral resolution survey will allow us to characterise turbulence (and kinematics) to an unprecedented level. A catalogue of OH masers will also be provided.

In the X-ray domain, Frank Haberl reviewed the status of population studies from the XMM-Newton surveys of the Magellanic Clouds and elaborated on future prospects using the eROSITA instrument on board the Spectrum-Roentgen-Gamma satellite. In particular, he highlighted studies of a large sample (~ 120) of high-mass (Be) X-ray binaries in the SMC, correlated with star formation at 25–60 Myr, where only half of them are pulsars. The expected exposure time of eROSITA across the Magellanic Clouds during the course of the survey, details about the instruments, its performance, and the first light commissioning image were also presented. To conclude this session, Knut Olsen presented the Rubin Observatory Legacy Survey of Space and Time (LSST) which is due to begin in 2023 at Vera C. Rubin Observatory. The proposed science case for observing the Magellanic Clouds makes use of the three main advantages of the telescope: i.e., wide, fast and deep. It addresses a broad range of questions that encompass most of the topics discussed in the meeting so far. It also faces technical challenges, such as solving the problem of separating stars from galaxies in dense stellar fields, extracting photometry for objects in these fields, and defining the footprint and cadence of a multitude of repeated observations.

Main conclusions and ways forward

The workshop was a great success. It provided a crucial platform for the presentation of a state-of-the-art view of the Magellanic system, comparing and combining results from different teams and projects, and stimulating a discussion that brought us to a better understanding of our neighbouring galaxies and their role as important suppliers of material to the Milky Way halo, demonstrating and quantifying the processes related to galaxy interactions, as well as group accretion in general that may be applicable to more distant systems. The workshop enhanced the impact of the VMC ESO Public Survey in the context of other dedicated and complementary programmes, for example using CTIO telescopes, and the plans formulated for future consortium observations of the Magellanic Clouds using the Multi Object Optical and Near-infrared Spectrograph (MOONS) and 4MOST instruments (see, for example, Cioni et al., 2019).

Demographics

The 104 participants at the workshop came from 17 different countries. The majority were from the United States of America and Germany, with 20% each, followed by ESO, Italy, Australia and the United Kindgom with 10% each; about 60% of the participants were from ESO Member States. Of the attendees, 35% were female and the Science Organising Committee formulated a scientific programme that reflected this percentage. The selection of contributed talks was made without considering the gender of the applicants while invited talks were selected to include, where possible, female speakers. It is interesting to note that the percentage of female participants matched the percentage of females who delivered review presentations. In addition, the workshop had a good balance of career level and seniority. Each of the eight workshop sessions had three review talks and two talks from students.

Acknowledgements

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References

Cioni, M.-R. L. et al. 2019, The Messenger, 175, 55

Links

[1] Workshop programme: https://www.eso.org/sci/meetings/2019/magellanic_clouds.html
[2] 30 Doradus VMC image: http://www.eso.org/public/news/eso1033/

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Fellows at ESO

Marie-Lou Gendron-Marsolais

Born in Montréal, I grew up mostly in the Québec countryside, in the Gaspésie Peninsula, that wild piece of land larger than Belgium along the south shore of the majestic Saint Lawrence river in eastern Canada. I spent my childhood between the vibrant cultural life of Montréal and the thick conifer forest covered by snow for six months a year. Very curious, I knew about all the whale species in the world, I would make small experiments to grow plants in the corner of my bedroom window, and I read every book in the village library, imagining myself climbing the Himalayas in our snowy backyard.

My interest in stars and everything beyond came later, after I started enjoying maths in high school, encouraged by a generous teacher. I didn't know what I wanted to become yet, though most likely something related to science. However, "scientific researcher" was not among the options that came out of those career orientation tests, and I had some trouble identifying with "science geniuses" such as Einstein, Newton, Darwin, etc. — even if I admired them deeply. I continued to study science and found in physics an elegant mix of mathematical equations and concepts.

Despite the unclear path ahead, I started a bachelor's in physics in Québec city. Far from home, overwhelmed by the workload and the complexity of numerous new notions, I struggled a bit to find my place in this world. I got a summer job at the Mont-Mégantic national park, hosting a small research observatory with a 1.6-m telescope. I would do astronomy tours, describing all the wonders of our Universe to amazed crowds. It was great. I loved it and learned a lot having this constant connection to the night sky. I got to know the time just by looking at the stars and I would chase comets, auroras, transits and meteor showers. In the meantime, I developed a profound interest in telescopes, these impressive machines in remote and extreme locations. My relentless curiosity for the fundamental rules of our Universe drove me to do a master's in theoretical particle physics when for two years I played with elegant differential equations and laws of symmetry. Meanwhile, I was offered the


Marie-Lou Gendron-Marsolais

opportunity to do a PhD in astronomy at the Université de Montréal and I moved to an observational study of supermassive black holes.

I started working under the supervision of Julie Hlavacek-Larrondo, analysing observations taken with the Very Large Array, a set of 27 large antennas in New Mexico. It was very challenging — everything was so new, but I quickly caught up with the astronomy world and its vocabulary. My PhD project was focused on a galaxy cluster called Perseus, located 200 million light years away — relatively close for astronomy! Its "proximity" allowed us to take very detailed pictures of what was going on there. With radio observations, I would trace the light coming from the central supermassive black hole of each of those giant galaxies as well as the powerful jets they release. I spent hours staring at those strange, complicated structures, trying to understand their origin. Most of all, the striking beauty of what I was seeing gave me the strength to pursue my work. I loved the feeling of discovering potentially new structures in those observations and being the first human to set eyes on them.

I also had the chance to visit the Harvard-Smithsonian Center for Astrophysics for six months and to work alongside some of the people who invented my field of research. I learned to work with observations from the Chandra X-ray observatory and still remember today the feeling of excitement when I first took a look at data that had been taken from space! I also used the newly installed optical imaging Fourier transform spectrometer SITELLE at the Canada-France-Hawaii Telescope.

This broad range of experiences allowed me to effectively bridge between observations at different wavelengths and gave me a strong set of skills. It also allowed me to build a network of passionate collaborators who, over time, became a strong source of support and motivation.

In my free time, I became involved in the newly formed diversity committee of the physics department of the Université de Montréal. Through my involvement, I learned about the barriers and challenges faced by women in science and getting a better understanding of these issues as well as meeting other astronomers receptive to those ideas helped me find my place. Throughout my studies, I continued my involvement in scientific communication at every opportunity (for example, at science festivals, in schools or at "Astronomy on Tap" events, etc.) — each occasion giving me a burst of confidence and passion towards astronomy as I shared my work.

Over the years, I used many telescopes and visited the observatories of Maunakea and Kitt Peak, the Very Large Array and the Arecibo observatory... but the Atacama Desert had always been the ultimate dream for me. I moved to Chile in October 2018 to start an ESO fellowship with duties at the ALMA observatory. I soon found myself under the southern sky, in command of one of the most powerful telescopes in the world. Being among ESO's rich community of experts in observational astronomy represents a unique opportunity to conduct my research, while allowing me to further develop my professional skills. To date, I still pursue my work on the Perseus cluster of galaxies, every set of new observations revealing a variety of unexpected discoveries. And so my quest for knowledge continues and at the same time my sense of wonder flourishes.

Matias Jones

I was born in Chile, the world capital of observational astronomy and a key window from the Earth to explore the Universe. Just 30 minutes away from my home town of Santiago is a beautiful place called Cajón del Maipo, a place free of light pollution and with clear skies during most of the year. At the age of 14 I joined a group for astronomy and astrophotography. We used to go to Cajon del Maipo to do astrophotography using a 10-cm diameter telescope without a motor, so for long exposures we had to manually track the apparent movement of the stars in the sky. During those years I strengthened my passion for science and realised that I would follow a scientific career in my adult life.

A couple of years later, I entered university to study physics and astronomy and after five years, I got my bachelor's degree. Although I really love experimental physics and I really enjoyed building high-temperature yttrium-barium-copper-oxide superconducting materials or carbon nanoparticles in advanced physics labs, I knew that my future lay in astronomy. So, I started a master's thesis in astronomy at the Universidad de Chile in Santiago. During my master's, I used Type II-P supernovae as extragalactic distance indicators.

Matias Jones

After receiving a master's degree, I finally started a PhD in astronomy, also at the Universidad de Chile, but this time in the area of extrasolar planets. The goal of my PhD thesis was to search for and characterise planetary systems orbiting giant stars, using the radial-velocity method. The main idea behind this project was to study other evolved planetary systems to understand what might happen to our own Solar System after the Sun evolves into a red giant star. During my PhD, I spent dozens of nights at the La Silla observatory, mainly collecting high-resolution spectroscopic data using the Fibre-fed Extended Range Optical Spectrograph (FEROS) and the High Accuracy Radial velocity Planet Searcher (HARPS). I also spent two years at ESO in Chile thanks to the ESO studentship programme. It was during this time that I first had the chance to visit that unique and magical place called Paranal to work on a short observatory project. I really enjoyed those fantastic years at ESO, where I also had the chance to interact with world experts in different areas and to use different observing techniques and instrumentation, when they visited the ESO offices in Chile.

In 2013, I obtained my PhD and moved to the Astro-Engineering Center (AIUC) at the Universidad Católica in Santiago, where I worked on the construction of two high-resolution spectrographs aimed at detecting exoplanets, one of which has been in full operation at La Silla since 2016. The next step in my career was already pretty clear to me. After finishing my position at the AIUC, I applied to the ESO fellowship programme in Chile, having in mind that it would allow me to work with state-of-the-art instruments, deepening my knowledge of instrumentation and new observing techniques. Moreover, getting the chance to work with and operate instruments like the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO) or the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES+) was an additional motivation.

I started my ESO fellowship in 2016, with duties in Paranal. Although when I arrived at ESO I expected to work on high-resolution spectrographs, where I could contribute my previous experience in the design, construction and extensive use of these kind of instruments, I was also very motivated to learn new observing techniques and new instruments. I therefore took on a new professional challenge when I joined the team for the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) on the VLT, which is a high contrast imaging instrument. As a member of the SPHERE instrument team I had the chance to discover the fascinating world of direct imaging. However, this was not easy. I had to learn about extreme adaptive optics and observing techniques that were completely new to me. Although at the very beginning it was difficult to learn about this complex machine — which comprises three sub-instruments plus SAXO, the extreme adaptive optics module of SPHERE — now, after more than 3 years, I have become an expert in this instrument and I am currently the SPHERE Instrument Scientist (IS2). In addition, I am the instrument fellow of CRIRES+ and ESPRESSO, which recently arrived at Paranal and is currently at the commissioning stage.

So far, my experience of working at Paranal has been truly that of a dream come true. The motivation one gets working at the VLT with the most sophisticated instruments in the world, many times pushing the limits of the observational techniques, is simply unique and very rewarding. In addition to that, there is also the fact that the VLT is located in one of the most beautiful places I have ever seen; this simply makes the VLT at Cerro Paranal the most perfect combination. Even after almost 300 nights at Paranal, I don't miss a chance to look at those amazing sunsets, and to look at the endless deep and dark sky, full of mystery and magic during the night. To be honest, I could not think of a better place to work.

Personnel Movements

Arrivals (1 July–30 September 2020)

Europe

Calmette, Elsa (FR)	ELT Programme Office Support (Programme Control & Quality Assurance)
Chen, Jianhang (CN)	Student IMPRS
de Sa Freitas, Camila (BR)	Student IMPRS
Erkal, Jessica (IE)	Student IRC Grant
Escarlate, Nathalia (BR)	Information Systems Specialist
Paneque Carreño, Teresa (ES)	Student IMPRS
Prümm, Michael (DE)	Software Development Engineer in Test
Sánchez Menguiano, Laura (ES)	Fellow
Ward, Samuel (UK)	Student ORIGINS Excellence Cluster
Zak, Jiri (CZ)	Student IMPRS

Chile

Bordier, Emma (FR)	Student
Givovich, Alejandro (CL)	IT Specialist-Infrastructure
González, Rodrigo (CL)	Software Engineer
Gonzalez, Sergio (CL)	Maintenance Engineer
Otárola, Angel (CL)	Atmosphere Scientist
Saldias, Leslie (CL)	Librarian

Departures (1 July–30 September 2020)

Europe

Anderson, Richard (DE)	Fellow
Belfiore, Francesco (IT)	Fellow
Bhattacharya, Souradeep (IN)	Student IMPRS
Cheffot, Anne-Laure (FR)	Student
Hamanowicz, Aleksandra (PL)	Student IMPRS
Hayden-Pawson, Connor (UK)	Student
Hussain, Gaitee (UK)	Head of Editorial Team
Lamperti, Isabella (CH)	Student
Mc Manmon, Conor (IE)	Software Engineer
Sarazin, Marc (FR)	Applied Physicist
van der Burg, Remco (NL)	Fellow
Wylezalek, Dominika (DE)	Fellow
Zsidi, Gabriella (HU)	Student

Chile

Belmar, Francisco (CL)	Telescope Instruments Operator
Frantz, Michel (FR)	Support & Quality Assurance Group Leader
Gómez, María Eugenia (CL)	Librarian
Herrero-Illana, Ruben (ES)	Fellow
Kara, Jan (CZ)	Student
Kravchenko, Kateryna (UA)	Fellow
Navarrete, Julio (CL)	Telescope Instruments Operator
Poupar, Sébastien (FR)	System Engineer
Vera, Sergio (CL)	Telescope Instruments Operator
van Holstein, Rob (NL)	Student

José Francisco Salgado (josefrancisco.org)/ESO

The Very Large Telescope (VLT) on Cerro Paranal, with the Large and Small Magellanic Clouds majestically displayed overhead.


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