The Messenger

No. 192 | 2024

ESO's Extremely Large Telescope Progress Update
Paranal Instrumentation Plan Lessons Learned 2023
Mapping Galaxy Transformation with the MAGPI Survey

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The Messenger is published in electronic form twice per year. ESO produces and distributes a wide variety of media connected to its activities. For further information, contact the ESO Department of Communication at:

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ISSN 0722-6691

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Front Cover: A full Moon rises up from behind Cerro Armazones in the Chilean Atacama Desert, where construction of ESO's Extremely Large Telescope is underway. In this image we see the steel skeleton of the telescope dome eerily illuminated in the moonlight. It now stands at a towering 80 metres high; when completed, the whole structure will rotate 360 degrees to observe the night sky, all while weighing 6100 tonnes. Credit: J. Beltrán/ESO

DOI: 10.18727/0722-6691/5346

The Rise of the Giant: ESO's Extremely Large Telescope

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The European Southern Observatory's Extremely Large Telescope (ESO's ELT) stands as the cornerstone of ESO's ambitious vision to build a new facility capable of providing a paradigm shift in our understanding of the cosmos. ESO's ELT is swiftly advancing towards completion, having surpassed, in June 2023, the 50% completion milestone. Possessing unparalleled sensitivity and angular resolution thanks to its 39-metre main mirror, ESO's ELT holds the potential to revolutionise our perspective on the Universe, from the exploration of exoplanets to the detailed study of stellar populations, and from unravelling the mysteries of galaxy evolution to probing fundamental physics and cosmology.

Brief overview

ESO's Extremely Large Telescope (or the ELT) will be housed in a giant 92-metre-diameter dome, which will provide protection from the environment of Chile's Atacama Desert. The main structure of the telescope will hold its five mirrors and optics, including the enormous 39-metre primary mirror made of 798 individual segments. The ELT will be also equipped with cutting-edge instruments, designed to cover a wide range of scientific possibilities, analysing light by means of imaging and spectroscopy. Both telescope and instruments will employ sophisticated adaptive optics technologies to compensate for the turbulence of Earth's atmosphere and to ensure the sharpest images, some six times sharper than the James Webb Space Telescope can produce.

Progress

The construction of this technically complex project has reached a key milestone, now surpassing the halfway mark as estimated by Earned Value Analysis, i.e. comparing the progress achieved and actual deliverables to the overall baseline plan[1].

As described in detail by Pascal Martinez in this issue of The Messenger (p. 4), the assembly of the dome structure, with its familiar round shape, is almost completed and is now clearly visible on top of Cerro Armazones in the Chilean Andes; inside it, the telescope structure is taking shape. What has been for many years the domain of 'artist's impressions' is now a reality and progress can be followed via dedicated webcams on the ELT website[2].

The other area where huge progress has been made is the production of the optics, as described by Elise Vernet et al., also in this issue of The Messenger (p. 6). The manufacturing in Europe of the various optics subsystems is advancing at a staggering pace. More than 90% of the blanks and the related supports needed to assemble the 798 hexagonal segments that form the giant primary mirror (M1) have now been manufactured. The first 100 fully assembled and polished segments have been completed, reaching a surface quality better than specification at a few tens of nanometers (almost 5000 times smaller than a human hair), and the first 18 segments have already reached Chile[3]. Both the secondary (M2) and tertiary (M3) mirrors, each with a diameter of ~ 4 metres, have already been cast, M2 having almost completed the polishing process, and the mechanical cells that will hold the mirrors in place are in their final stages of production. The M4 and M5 mirrors that are at the core of the telescope's adaptive optics, capable of moving and adjusting their shape a thousand times a second to correct for distortions caused by air turbulence, are also in full production. And all six laser sources, another key component of the ELT's adaptive optics system, have been produced and delivered to ESO for testing.

The development and production of other crucial operational systems, such as the control system, the pre-focal stations and the assembly equipment for the ELT, are also progressing well, while the support infrastructure at Cerro Armazones and Paranal, including the technical building for mirror storage and coating and the photovoltaic plant, are already in full operation. In parallel to all this progress, the organisation has also set up an On-Site Engineering Department to provide, within the best matrix approach, the required resources for the final Assembly Integration and Verification phase.

As regards the instrumentation that will allow scientists to analyse the light collected by the telescope coming from distant planets, stars and galaxies, all four instruments — the Multi-AO Imaging Camera for Deep Observations (MICADO), the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI), the Mid-infrared ELT Imager and Spectrograph (METIS) and the Multiconjugate adaptive Optics Relay For ELT Observations (MORFEO) — are now in their final design phases, and manufacturing of some key components has already started. At the same time, the future instruments the ArmazoNes high Dispersion Echelle Spectrograph (ANDES) and the multi-object spectrograph MOSAIC have started their preliminary design.

Completion and first light

While the journey to reach this halfway point has been marked by meticulous design finalisation, prototyping, and extensive testing campaigns, and also hindered by the challenges posed by the COVID-19 pandemic when the site and many production lines closed for several months, the timescale to complete the remaining 50% of the project is estimated to be shorter. Indeed, all production processes are now fully operational and running at full speed, while the planning for the final integration of all the subsystems to assemble and commission the telescope is in place. In just a few years, in 2028, ESO's ELT is expected to start scientific observations, and with its 'biggest eye on the sky' it is poised to unravel profound mysteries of the Universe and our place within it.

Links

[1] ESO press release "ESO's Extremely Large Telescope is now half completed": https://www.eso.org/public/news/eso2310/
[2] ELT webcams: https://elt.eso.org/about/webcams/
[3] ESO press release "First segments of the world's largest telescope mirror shipped to Chile": https://www.eso.org/public/news/eso2319/

DOI: 10.18727/0722-6691/5347

ESO's Extremely Large Telescope Dome and Main Structure Update

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In the ongoing saga of constructing an 80-metre-high dome and an expansive telescope structure for ESO's Extremely Large Telescope (ELT), the narrative unfolds as a testament to human resilience and determination. Originating from a contract signed in 2016, the Dome and Main Structure (DMS) project has survived financial restructuring, partner bankruptcy and global upheaval caused by the COVID-19 pandemic and market fluctuations that resulted in a complex contractual and commercial situation. The DMS project includes the construction of both the internal telescope structure that supports the telescope mirrors and the instruments, as well as the external dome that provides protection against the harsh conditions of the Atacama Desert. Following the design phase, the project started with the construction of the foundations and of the gigantic dome. In September 2023 a new chapter began, marked by the start of the construction of the telescope structure, a phase demanding an unprecedented level of precision and constant supervision by the ESO team on site. The design, born from a collaboration of many disciplines, is now consolidated and frozen, setting the stage for a race against time to achieve the highest possible level of quality demanded by the 'biggest eye on the sky'.


ESO DMS team

Figure 1. Dome and Main Structure construction status (January 2024).

Dimensional marvels and technical precision

The monumental dome stands 80 metres high, with a commanding 92-metre diameter. It requires nearly 80 000 pieces of steel to come together with no fewer than 500 000 bolts. It sits on a concrete foundation of 21 000 tonnes, fully isolated from seismic accelerations.

The 6200 tonnes of the dome rotating mass will protect the 4600-tonne telescope structure with all its mirrors and instruments. Rotating such a complex structure without inducing any vibrations in the telescope has required many hours of design and analysis that have resulted in 36 driving trolleys, each the size of a small 27-tonne truck. The high level of protection of the telescope is ensured by the complex cladding structure representing 30 000 m^2 of material that shields the precious mirrors and instruments from light, dust, water and lightning. The design has required complex tests to validate the non-propagation of dust and resistance to lightning, and even required dropping big lumps of ice on the structure to demonstrate its resistance to falling icicles.

The telescope structure is an engineering marvel that required no fewer than four complex design reviews, generating thousands of questions and actions to be analysed before the construction drawings could finally go to production. Pointing the telescope towards the celestial heavens demands an unparalleled level of precision. The azimuth and altitude tracks, machined and aligned with micrometric accuracy, are now part of a race against time. The three azimuth tracks (the largest one having a diameter of 54 metres) that allow the telescope to rotate on its base are now fully installed. And the 27-metre-diameter curved altitude tracks that allow the telescope to move in the vertical direction require machining accuracies that have never been achieved before — and are still not fully demonstrated — to maintain a constant film of oil a few tens of microns thick that will allow the structure to point to the stars in a precise and smooth fashion.

Manufacturing and shipping thousands of tons of precision material against a ticking clock

Putting together a large and complex dome and the most technically challenging telescope on the planet on top of a mountain in an unforgiving environment requires more than just steel, it requires a degree of preparation and logistics that is very uncommon in this kind of industrial project. The level of quality implemented by the contractor and by ESO in terms of inspection and tests is unprecedented; for hundreds of hours experts are present at the contractors' premises to inspect every weld and painted surface, and to test every mechanism before it is packed and shipped. At the time of writing, the complete dome structure has been manufactured and shipped to Chile and only eight beams out of 16 000 required some local welding, a testament to the high quality achieved during manufacturing. About 70% of the dome mechanisms (motors for the windscreen, lifts, cranes etc.) — largely off-the-shelf components — have been procured and are currently being shipped. More than 90% of the structure dome has now been completed (see Figure 1).

The telescope structure, manufacturing of which started in summer 2022, has now reached ~ 40% and is being shipped to the site for assembly in a just-in-time mode. Pre-assembly in Europe is done in a systematic manner to ensure that no corrective actions will be required on site. The size of the elements is such that entire vessels have been used to transport the DMS components across the ocean, and unloading those vessels and bringing the material to the site on Armazones has sometimes required up to two months of trucking with police escorts.

A giant growing towards the sky

Having been closed for a year during the COVID-19 pandemic, the site reopened in June 2021 and construction restarted. For some reason, the clock is always ticking faster on a construction site. On average no fewer than 200 people are needed to assemble this giant on top of the Armazones mountain. The top platform itself, the Armazones Top Platform (ATP), where the ELT sits, is too small to host all; a basecamp – the Armazones Basecamp (ABC) – had to be built at the bottom of the mountain to accommodate all the workers with all the logistics and also the very important storage and pre-assembly areas that cover a total area of 65 000 m^2. The 70-tonne modules are brought from the ABC to the ATP, some 7.4 kilometres away, using Self Propelled Modular Transport systems, taking approximately two hours for each trip. Up to seven cranes, the biggest one with a capacity of 600 tonnes and with a boom reaching 120 metres in height that allows lifts of 90 metres, are being regularly used at the ATP and another three at the ABC. Having such a permanent ballet of cranes combined with working at height requires uninterrupted vigilance. With safety on top, quality, quality, and quality are the goals that drive all 16 ESO staff on site, along with the other 20 ESO DMS experts in Europe, who continuously follow the work of the contractors.

This massive industrial setup in the middle of the desert saw the first 2000 tonnes of the dome structure, between the 14-metre and 66-metre levels, erected in only four months. With the Main Structure erection started in December 2023 and the Azimuth Floor now fully installed, we are all looking forward to the end of 2024 when the dome will be fully closed and sealed, the Main Structure erected, and the gigantic air conditioning system (heating, ventilation and air conditioning) under commissioning.

Looking ahead another year, 2025 will see the installation of mechanisms and systems commissioning. In early 2026 the acceptance activities will start, lasting until July 2026, the date set for the Provisional Acceptance when the DMS will finally be fully handed over to the ELT programme by the contractor, ready to begin the assembly of the mirrors that will transform this monumental structure into a functioning telescope, the biggest eye on the sky that humanity has ever built.

ESO's Extremely Large Telescope (ELT) is quickly coming together before our eyes. In this webcam image over Cerro Armazones in Chile from 16 February 2024, the setting Sun illuminates the first pieces of cladding installed on the ELT dome. The hemispheric structure of the dome will be encased in thermally insulated aluminium cladding to protect the delicate mirrors from the harsh desert environment, enabling the world's biggest eye on the sky to capture the cosmos in never-before-seen detail for a long time to come.

DOI: 10.18727/0722-6691/5348

ESO's Extremely Large Telescope Optics Update

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The Extremely Large Telescope is at the core of ESO's vision to deliver the largest optical and infrared telescope in the world. We present an updated status report on the five mirrors of the telescope, focusing on the challenges and the progress made in the last few years.

Background: how the ELT works

The optical design of ESO's Extremely Large Telescope (ELT) is based on a novel five-mirror scheme capable of collecting and focusing the light from astronomical sources and feeding state-of-the-art instruments to carry out imaging and spectroscopy. The light is collected by the giant primary mirror (M1, 39.3 metres in diameter), relayed via the secondary and tertiary mirrors, M2 and M3 (each of which has an approximately 4-metre diameter), to M4 and M5 (the core of the telescope adaptive optics). The light then reaches the instruments on one of the two Nasmyth platforms.

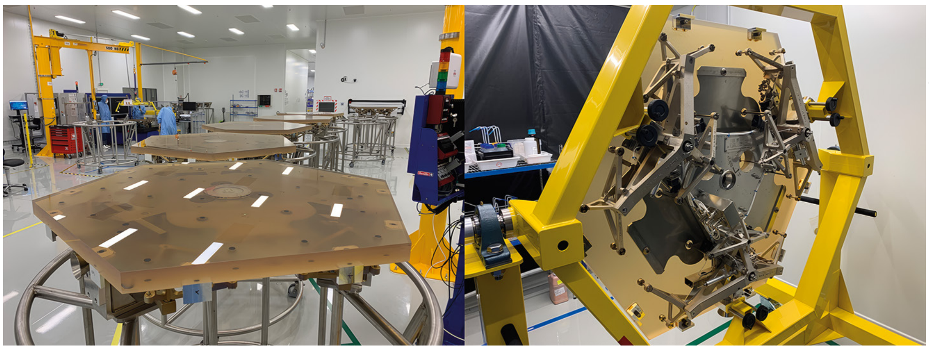
This design provides an unvignetted field of view (FoV) with a diameter of 10 arcminutes on the sky, or an area of about 80 square arcminutes (i.e., about one ninth of the area of the full Moon). Thanks to the combined action of M4 and M5, the ELT will have the capability to correct for atmospheric turbulence as well as the vibration of the telescope structure induced by its movement and the wind. This is crucial to allow the telescope to reach its diffraction limit, which is about 8 milliarcseconds (mas) in the *J* band (at $\lambda \sim 1.2$ μm) and about 14 mas in the *K* band (at $\lambda \sim 2.2$ μm), thereby providing images 15 times sharper than the Hubble Space Telescope, and six times sharper than the James Webb Space Telescope.

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

The 39-metre primary mirror

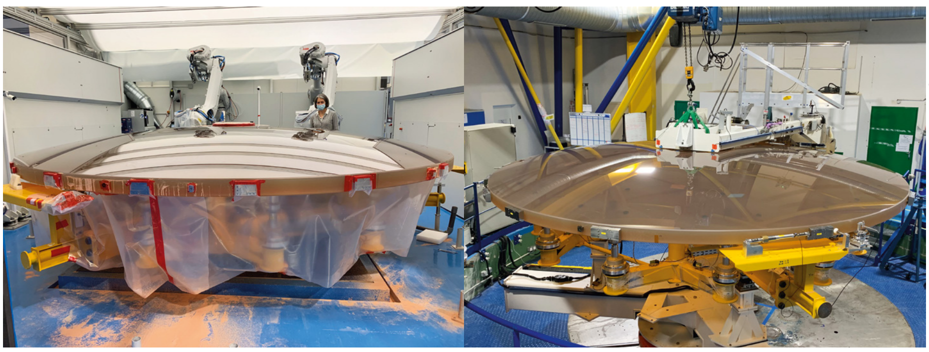
The production of the full M1 mirror was approved by ESO's Council in 2017 (Cirasuolo et al., 2018). M1 is made of 798 Segment Assemblies, each one made up of a polished mirror Segment, integrated to a mechanical Segment Support, and equipped with twelve Edge Sensors. Each Segment Assembly is installed on a subcell, made of a Fixed Frame Assembly and three position actuators (PACTS). In operation, Segment Assemblies need to be exchanged daily for maintenance and re-coating. For that purpose, an additional set of Segment Assemblies have been ordered (the seventh sector), so in all 931 optics are procured. In total, more than 10 000 components have been ordered to build M1.

Schott (Germany) was contracted to manufacture the Zerodur© blanks by the end of 2017 (the 'glass'). The first 18 blanks were delivered to Safran Reosc (France) in May 2019. Production by Schott has been steady since then. By the end of 2023 more than 800 blanks had been finished and accepted. This represents more than 85% of the full production. Schott will complete the manufacturing of the blanks by June 2024.



Safran Reosc

Figure 1. M1 segment polishing at Safran. Left: the segments are waiting for final inspection. Right: Segment support control after its integration with the mirror.



Safran Reosc

Figure 2. The M2 mirror after its last polishing run: left, on the polishing stand and right, during interferometric measurement.

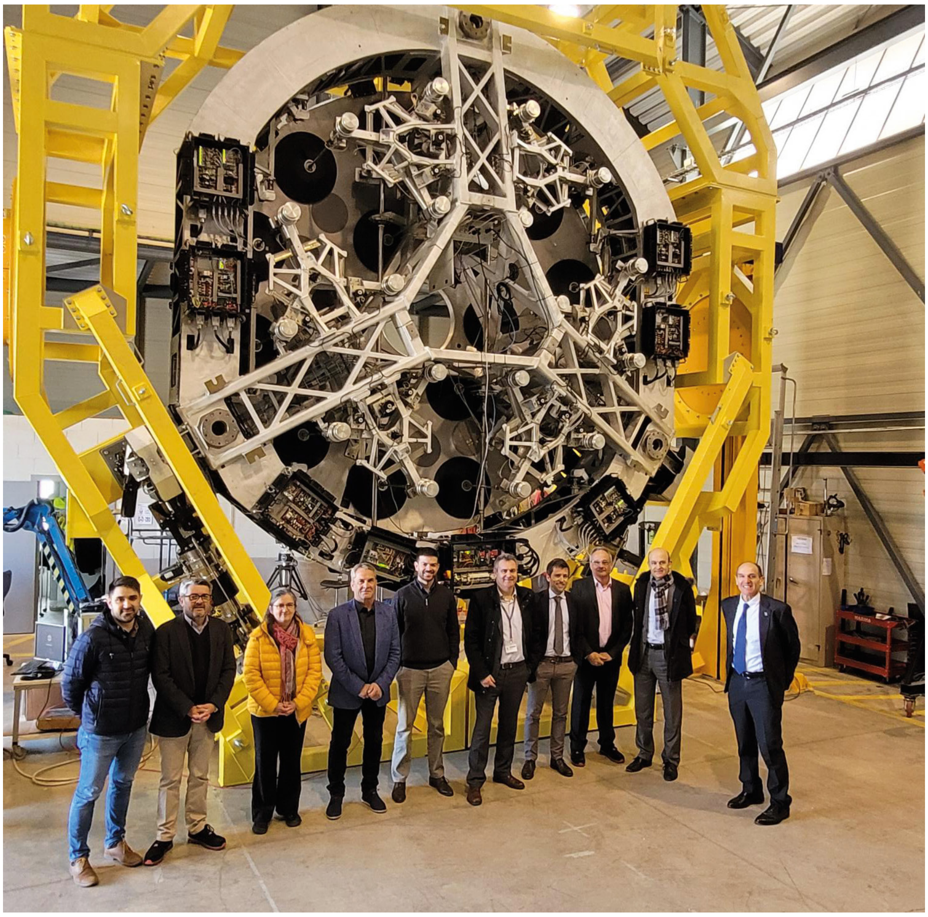
The contract to produce the Segment Supports and Fixed Frame Assemblies was signed in April 2018 with VDL (the Netherlands). Production started with 18 validation models to qualify the production and verification means, to fine-tune the manufacturing procedures, and to make the integration at Safran Reosc straightforward and reliable. Production was then ramped up, and the first deliveries to Safran Reosc took place in September 2019. Today 85% of the production is finished and accepted. VDL expect to complete the production by mid-2024.

The Segment Blanks and Segment Supports are being delivered to Safran Reosc to produce the 931 Segment Assemblies. The main production steps are as follows:
– First, the segment mounting interface pads are bonded to the circular Zerodur© blank.
– The blank is then fine-ground aspherical and polished to sub-micron accuracy.
– Thereafter the segment is cut to a near-hexagonal contour and Edge Sensor pockets are machined.
– The Edge Sensor interface pads are bonded in their pockets, and the segment is integrated onto its Segment Support.
– The Segment Assembly is then finish-figured to final tolerances by ion beam figuring.

Optical testing is performed with the optical surface horizontal and looking upwards, by short cavity Fizeau interferometry against a reference test plate combined with computer generated holographic correctors (CGH). The optical quality requirements apply to the fully integrated Segment Assembly, over the whole Segment surface (there is no segment clear aperture).

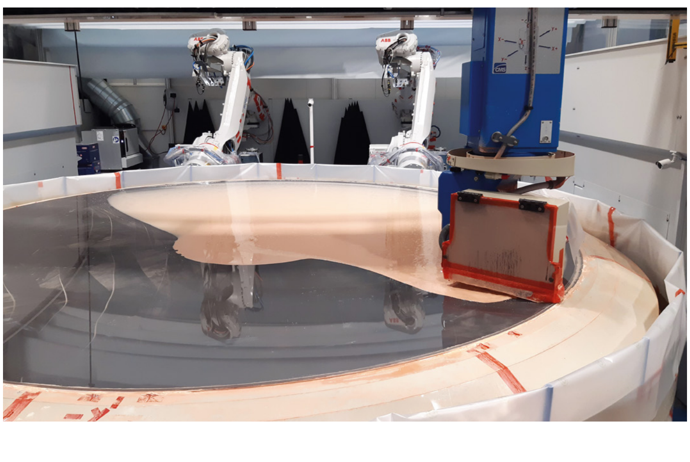
The Segment Assembly production contract with Safran Reosc was kicked off in September 2017. Safran has set up for the purpose an existing 4000-square-metre building at their facilities in Poitiers (France). In parallel they designed, procured, and installed the production and test means. These are highly automated to maximise the production rate. All processes went through extensive testing and fine-tuning until the whole production line was qualified, and the first 18 validation Segment Assemblies were produced, allowing manufacturing ramp-up.

The first Segment Assembly was finished in May 2022 and by the end of 2023 more than 180 segments had entered production and more than 110 have been finished and packed, waiting for acceptance and shipment (Figure 1). The first 45 segments were accepted in December 2023 and the 18 validation segments were delivered to Paranal on 12 January 2024. Safran Reosc is continuing to ramp up production and has achieved a



Sener Aerospacial

Figure 3. The M2 Cell in final testing.



Safran Reosc

Figure 4. The M3 mirror during the second grinding run.

Sener Aerospacial

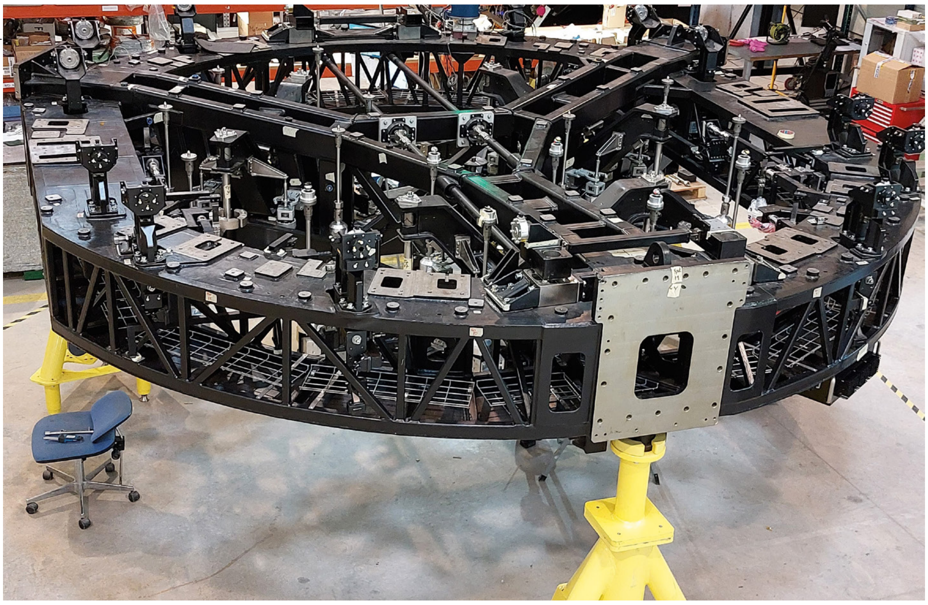


Figure 5. The M3 Cell in integration.

throughput of about four Segment Assemblies a week, the objective being to reach five a week in the first quarter of 2024. At this rate the production of the 931 Segment Assemblies should be completed by mid-2027.

The Fames consortium, composed of Fogale (France) and Micro-Epsilon (Germany), started production of the Edge Sensors three years after the signature of the contract and the first set of Edge Sensors was delivered in January 2021. Production has been continuing steadily and so far more than 2900 Edge Sensors, equivalent to 65% of the total, have been delivered to Chile. Production will be finished before summer 2024.

The contract for the procurement of 2500 PACTs was signed in June 2017 with Physik Instrumente GmbH & Co. KG (Germany). The final design was completed by mid-2021 and the first units were ready for verification a few months later. Following intensive testing and some final adjustments, Physik Instrumente were able to start mass production. The pre-series PACTs were accepted in the first quarter of 2023, and by the end of 2023 nearly 1000 PACTs had been accepted, about 40% of the total required. Production continues at full speed and its completion is foreseen before summer 2024.

The secondary and tertiary mirrors

The secondary and tertiary mirrors are two four-metre-class mirrors. The secondary is highly convex and aspheric while the tertiary mirror is concave and slightly aspheric (Cayrel et al., 2019).

Safran Reosc started to grind the M2 Blank in March 2019. The blank went through several grinding runs followed by four polishing runs (Figure 2). At the time of writing the mirror surface quality is about 60 nm RMS, almost within specification as regards the low-order frequencies. Safran Reosc has started the final figuring steps, including correction and smoothing the high-frequency residuals. It is expected that polishing of the M2 Mirror will be finished by autumn 2024.

In parallel Sener Aerospacial (Spain) passed the final design review of the M2 and M3 Cells — that will hold the mirrors in place — by the end of 2019, and the manufacturing readiness review in March 2020. They started the integration of the M2 Cell in early 2022. Today the M2 Cell is in final acceptance testing and it is expected to be delivered by summer 2024 (Figure 3). Sener Aerospacial is verifying the compliance of the cells using aluminium dummy mirrors. The M2 Cell will then be shipped to Safran Reosc, the M2 mirror will be integrated on the cell and the full assembly will be optically tested. This final verification, called system test, will take place between the end of 2024 and early 2025.

The M3 mirror is at a less advanced stage as priority is being given to the M2 mirror and both mirrors share a common production method. M3 has already been through two grinding runs (Figure 4), and it is now waiting for the acceptance of the M2 mirror to get back in production. The M3 Cell is more advanced than its mirror. It is currently in final integration (Figure 5) and it is expected to be finished by the end of 2024.

The quaternary mirror

The M4 mirror provides the main adaptive optics of the telescope. M4 will use more than 5000 actuators that can change the shape of the mirror up to 1000 times per second. In combination with M5, M4 is therefore the core of the adaptive optics

Adoptica

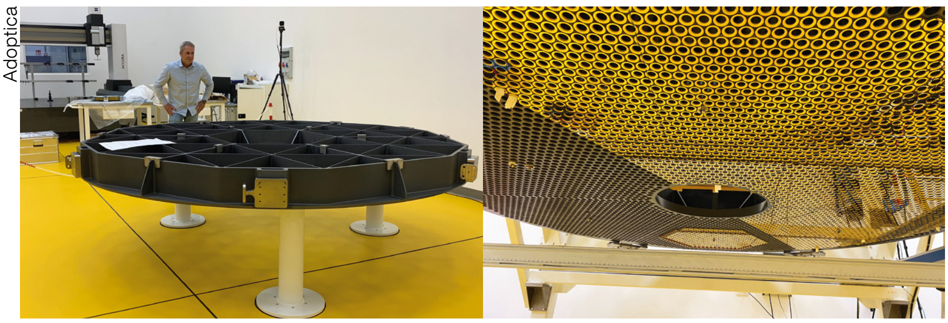


Figure 6. The M4 reference structure during integration of the mounting interfaces (left picture) and of the borosilicate tiles (right picture) on the M4 reference structure.

Safran Reosc

Figure 7. Shell inspection before final cutting.

Sener Aerospacial

Figure 8. The M5 Cell with the dummy mirror.

Mersen Boostec

Figure 9. The M5 Blank under inspection after grinding of the front face by Mersen Boostec.

of the ELT and, with a diameter of 2.4 metres, it will be the largest adaptive mirror ever built. It was one of the first contracts started under the ELT project. The Final Design Review was passed in 2018 and the Adoptica consortium (Microgate and ADS International, Italy) began procuring the various components. In 2019 the M4 SiC reference structure was brazed at Mersen Boostec (France) and Adoptica began procuring all the other parts of the unit (Vernet et al., 2019). The reference structure front surface was lapped by AMOS (Belgium) and delivered to Adoptica by the end of June 2022. Adoptica completed the bonding of the mounting interfaces and is bonding borosilicate tiles onto the reference structure, which will form capacitive cavities with the M4 thin shells for position feedback (Figure 6). This task is very delicate, requiring tight positioning accuracy, and it will take quite a long time given that several thousand tiles have to be bonded. Adoptica is planning to complete it in spring 2024. In parallel, Safran Reosc completed the production of the twelve M4 thin shells (two sets of six shells). The last ones were delivered in July 2023 (Figure 7).

All the other sub-systems are ready to be assembled with the reference structure. The unit integration activities will be finished before summer 2024 and Adoptica will then start the calibration phase of the full system followed by the performance verification. Technical acceptance in Europe is foreseen in early 2026 and acceptance in Chile one year later.

The fifth mirror

M5 is a flat elliptical mirror of diameter 2.2 metres on the minor axis and 2.7 metres on the major axis (Vernet et al., 2021). M5 is the field stabilisation mirror of the telescope; it will tip-tilt to correct for vibrations of the telescope structure induced by its motion and by the wind. This is achieved by three actuators which move the M5 mirror two to three times a second.

The M5 Cell is being designed and manufactured by Sener Aerospacial. The Final Design Review was passed in February 2022. All the procurements and the M5 Cell integration were completed during the last months of 2022. The M5 aluminium dummy mirror was mounted on the M5 Cell in February 2023, allowing Sener Aerospacial to fine-tune the system and reach the required performance. Today the cell is in final testing (Figure 8). Acceptance of the cell is foreseen in March 2024.

The M5 Blank is being made by Mersen Boostec as a subcontractor of Safran Reosc. It is quite challenging and is a world first, consisting of making six lightweight SiC petals, coating them with a thick CVD SiC layer, and brazing them together with a very high accuracy. The blank manufacturing started in 2021 and the six petals were brazed together in March 2023. After extensive verification of the brazed blank, the front surface has been ground, in two steps between July and November 2023 (Figure 9). Mersen Boostec is currently grinding the support interfaces, the last step before acceptance of the blank and transfer to Safran Reosc. This is planned in March 2024. Once at Safran Reosc, the blank will be equipped with its axial and lateral support before the polishing and final figuring process are started. The mirror assembly is expected to be delivered to Chile the first quarter of 2028.

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Cayrel, M. et al. 2019, The Messenger, 176, 13
Vernet, E. et al. 2019, The Messenger, 178, 3
Vernet, E. et al. 2021, The Messenger, 185, 3

Astronomical Science

ESO/VPHAS+ team. Acknowledgement: CASU

Astronomers are well-known for naming objects with odd conventions, and the cometary globule GN 16.43.7.01 seen in this image is no exception. Cometary globules have nothing to do with comets aside from appearance: they are named for their dusty head and elongated, dark tail, as seen in this image taken with the VLT Survey Telescope (VST) hosted at ESO's Paranal Observatory in Chile.

DOI: 10.18727/0722-6691/5349

Mapping Galaxy Transformation with the MAGPI Survey

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The Middle Ages Galaxy Properties with IFS (MAGPI) survey is an ongoing ESO Large Programme combining medium-deep Multi Unit Spectroscopic Explorer (MUSE) observations and an extensive library of simulated data to understand galaxy assembly over the past four billion years of cosmic time. Thanks to the combination of MUSE and the GALACSI adaptive optics system, MAGPI is delivering spatially resolved kinematic, star formation, and stellar population maps for hundreds of galaxies at intermediate redshift. By targeting galaxies across a range of environments, MAGPI will provide a unique perspective on the physical mechanisms responsible for transforming galaxy morphologies and kinematics at late cosmic times.

Galaxy transformation during the assembly epoch

Current models for the formation of massive galaxies (> 10^{11} solar masses) suggest two distinct evolutionary phases. At early times their growth is expected to be driven by rapid *in-situ* star formation fed by the accretion of gas from the cosmic web. The relative balance of accretion, star formation, and feedback during this first ‘formation’ phase leads to a tight linear relation between stellar mass and star formation rate for normal star-forming galaxies. Galaxies appear to maintain a relatively high star formation duty cycle (30–70%) until their star formation is quenched, either through the removal of a suitable gas reservoir or suppression of gas cooling (for example, Man & Belli, 2018). This quenching process, which marks the transition to the second phase of galaxy formation, leads to the build-up of a massive, passive galaxy population whose evolution is then dominated by the assembly of stellar mass formed *ex-situ* through mergers.

Spatially and spectrally resolved observations over the past several decades have sharpened our view of the early formation phase. Among other things, deep observations with the Very Large Telescope’s (VLT) Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI), the *K*-band Multi Object Spectrograph (KMOS), and the Atacama Large Millimeter/submillimeter Array (ALMA) during the epoch of peak star formation at z = 2–3 have highlighted that most stars appear to form in turbulent, gas rich, marginally stable discs (Förster Schreiber et al., 2009; Wisnioski et al., 2015; Stott et al., 2016; Liu et al., 2019). These kinematic results are supported by JWST imaging in the rest-frame near-infrared that highlights an abundance of disc galaxies in the early Universe (Ferreira et al., 2022, 2023; Kartaltepe et al., 2023; Nelson et al., 2023). Taken together, these observational results are consistent with the early stages of massive galaxy formation described previously, i.e., in which growth is dominated by *in-situ* star formation.

At late times, as the cosmological accretion rate falls, the dominant pathway for galaxy growth is expected to transition from *in-situ* star formation to the assembly of stars formed *ex-situ*. As well as providing a pathway for continued growth in the absence of ongoing star formation, galaxy-galaxy interactions are expected to transform early disc-dominated systems into the diverse range of morphologies mapped by the Hubble sequence in the nearby Universe. Simulations predict that repeated minor-merging in particular can account for the lack of massive, compact, and rotationally supported galaxies seen locally. These predictions are borne out by observations that suggest massive galaxies today are a factor of 3–5 larger and have substantially lower angular momentum than their expected progenitors at $z > 1$ (for example, Belli, Newman & Ellis, 2014; Bezanson et al., 2018). Detailed investigations of the stellar populations in nearby galaxies — especially radial profiles of age, metallicity, and alpha-element abundance — further support a picture in which the accretion of low-mass, gas-poor satellites is the primary driver of massive galaxy evolution during this assembly epoch.

While the outcomes of the assembly process are made manifest in the diversity of galaxies we observe in the nearby Universe, understanding when and how this diversity developed is challenging. Observations of nearby galaxies using integral field spectrographs (IFS) leverage a combination of resolved kinematics and stellar populations to untangle this story using archaeological methods. Kinematic features and metallicity gradients of stars and gas can reveal hints of the evolutionary path for an individual galaxy (Taylor & Kobayashi, 2017; Tissera et al., 2018; Martig et al., 2021), the details of which are further expected to depend on the properties of its host environment (Foster et al., 2021). It is therefore crucial to study massive galaxies in a resolved manner at different cosmic times and across a range of different environments.

It is with this context in mind that we have undertaken the Middle Ages Galaxy Properties with IFS (MAGPI) survey, which represents one of the first systematic studies of resolved stellar and gas properties at intermediate lookback times. Unlike previous surveys, MAGPI utilises the unique capabilities of the Multi Unit Spectroscopic Explorer (MUSE) and the Adaptive Optics Facility (AOF) of the VLT to obtain data with a physical resolution comparable to that of local IFS surveys such as Mapping Nearby Galaxies at APO (MaNGA; Bundy et al., 2015) and the Sydney-AAO Multi-object Integral field spectrograph (SAMI) survey (Bryant et al., 2015). These data therefore enable a unique comparison of resolved galaxy properties across a range of environments and lookback times.

Data

The MAGPI survey comprises two parts. The first is a set of medium-deep IFS observations using MUSE and the GALACSI adaptive optics system to probe massive galaxies and their

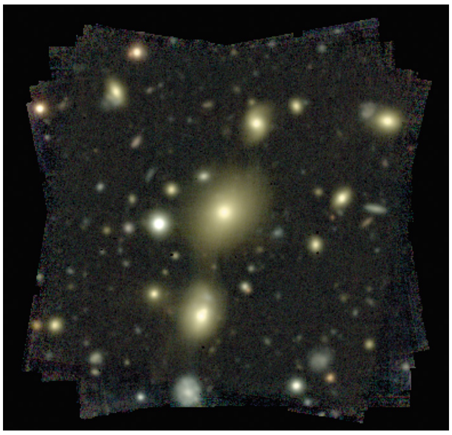

Figure 1. Mock Sloan Digital Sky Survey (SDSS) *gri*-band image computed using MUSE data for the MAGPI 1501 field.

environments at $z \sim 0.3$. The second is a suite of mock IFS data tailored to match these observations and facilitate a detailed comparison with state-of-the-art cosmological simulations.

The MAGPI MUSE survey

The observational component of MAGPI leverages the wide field of view and excellent image quality delivered by GALACSI+MUSE to survey 56 independent fields. Each field is centred on a massive ($M_\star > 7 \times 10^{10}$ solar masses) 'primary' galaxy at $0.25 < z < 0.35$ and its surrounding environment. All observations are carried out using MUSE in the WFM-AO mode. Potential targets were first identified within the Galaxy And Mass Assembly (GAMA) survey (Driver et al., 2011) G12, G15 and G23 fields to span a range of environments and galaxy colours, with the final selection driven by the availability of suitably bright tip-tilt stars from Gaia DR2. As of December 2023, observations have been completed for 49 of the 56 target fields.

The average exposure time for any given section of the ~ 1-arcmin^2 MUSE field is four hours, and data reduction for the survey is carried out using the ESO MUSE data reduction pipeline (Weilbacher et al., 2020). The final reduced and calibrated data cubes are photometrically complete down to $i_{AB} \sim 26$ mag (3σ), and spectroscopically complete down to $i_{AB} \sim 22$ mag.

The median *i*-band image quality is 0.55 arcseconds, assessed either using point sources available in a subset of the fields or via reconstruction of the adaptive optics point spread function using MUSE-PSFR (Fusco et al., 2020). An example of the reduced data for one field, MAGPI 1501, is shown in Figure 1.

Given the physical extent of the MUSE field of view projected at $z \sim 0.3$ (~ 270 kpc), each MAGPI field includes not only the galaxy of interest, but a host of satellite and background galaxies that facilitate a range of additional science. Sources in each field are identified and catalogued using ProFound (Robotham et al., 2018) based on a series of white-light and narrow-band images, and subsequently have redshifts manually assigned using the redshifting software package MARZ (Hinton et al., 2016). Across the current survey this process has identified ~ 400 low-mass satellite galaxies in our redshift range of interest ($0.25 < z < 0.35$) and another > 1200 objects at $z > 0.4$, all with secure redshifts.

The MAGPI theory survey

From the outset it was clear that disentangling the various internal and external processes driving galaxy transformation at late times would be challenging given observational data alone. For this reason, a key deliverable of MAGPI is the associated theory survey, in which mock MUSE observations have been constructed for a growing number of large, cosmological hydrodynamical simulations. Currently this includes Evolution and Assembly of GaLaxies and their Environments (EAGLE; Schaye et al., 2015; Crain et al., 2015), IllustrisTNG (Pillepich et al., 2018; Nelson et al., 2019), Magneticum (Teklu et al., 2015; Dolag, Komatsu & Sunyaev, 2016), and HorizonAGN (Dubois et al., 2016).

Current cosmological models are extremely complex, with a variety of recipes to account for effects below the resolvable scales in the model. An example of this complexity for the suite of simulations currently included in the MAGPI theory survey is demonstrated in Figure 2. While all simulations include the key ingredients necessary for galaxy formation and evolution — gravity, gas cooling, star formation, stellar and black hole feedback etc. — the specific recipe for each ingredient used can vary substantially. All of these elements are important for reproducing ensemble properties of the galaxy population (for example, stellar

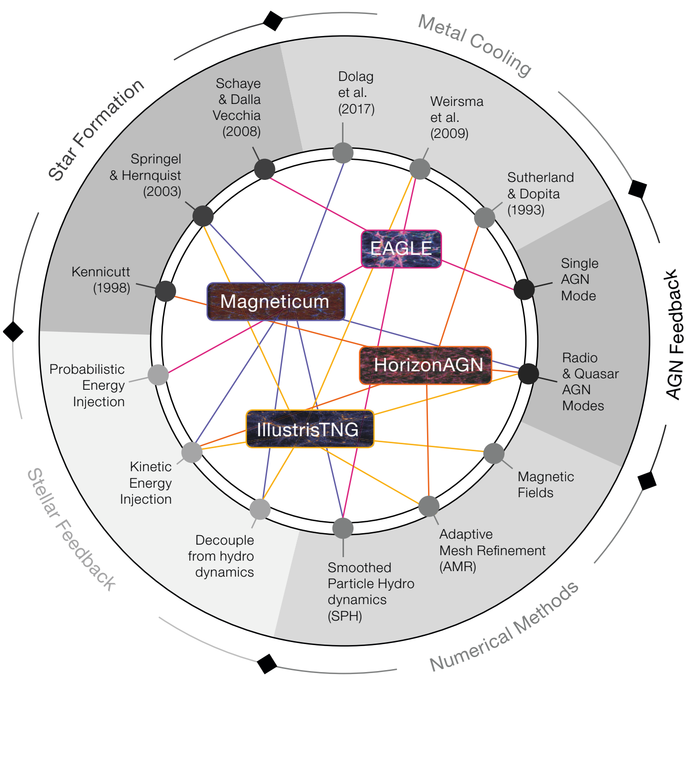

Figure 2. Demonstrating the basic ingredients for a cosmological model of galaxy formation and evolution. The models explored by the MAGPI Theory Stream are shown in the centre. Each model has links to the specific recipe used for each necessary ingredient. This makes clear the complexity of comparing different models and justifies the necessity of comparable data products. Figure adapted from Harborne et al. (in preparation).

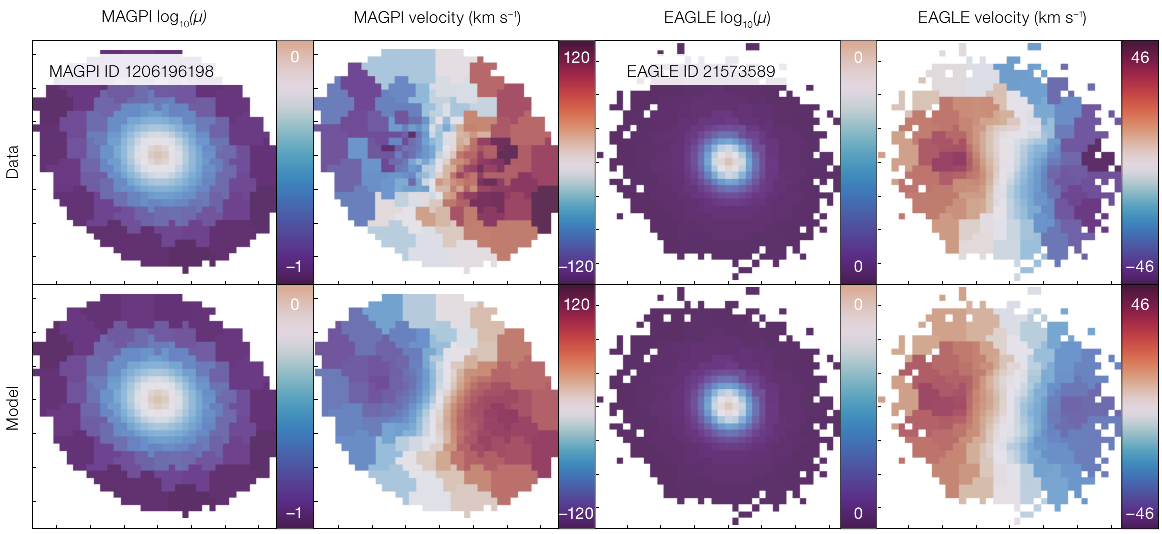

Figure 3. Two-dimensional surface brightness (first and third columns) and velocity (second and fourth columns) maps for one MAGPI galaxy (on the left) and one EAGLE galaxy (on the right). The top rows show data obtained from MUSE and analogous data from the EAGLE simulation produced using SimSpin. The bottom row shows the reconstruction of these data using DYNAMITE. Figure adapted from Derkenne et al. (in preparation) and Santucci et al. (in preparation).

mass, size etc.), but disentangling the effects of these sub-grid recipes and their relation to our observations requires a like-for-like comparison.

In order to build a comparable theory sample we have been using the open-source package SimSpin (Harborne, Power & Robotham, 2020; Harborne et al., 2023) to generate mock MUSE observations of simulated galaxies. This code is designed to be agnostic to the type of simulation input, including support for many flavours of different hydrodynamical models and various numerical methods; it is also easily configured to mimic a range of different instruments including MUSE, SAMI, and the MaNGA instrument. Output mock observations can be produced in the format of spectral data cubes, such that reduction pipelines and kinematic line-fitting software can be optimised and tested. SimSpin can also produce kinematic maps comparable to those output by our data analysis pipeline, but without the fitting procedure. This enables fast iteration across a range of projection angles and seeing conditions, for investigation into specific features and their evolution throughout cosmic time.

Key science

MAGPI data allow us to map kinematics and stellar populations across a range of galaxy spatial scales and environments, and a full outline of the science goals for the survey can be found in Foster et al. (2021). Here we highlight recent progress in several areas which seek to connect these data to observations at both low and high redshift.

Stellar dynamics

Stellar kinematics are powerful tracers of galaxy formation and evolution, as they encode the full history of processes impacting galaxy growth over cosmic time. Early results combining MAGPI with SAMI at $z = 0$ and the Large Early Galaxy Astrophysics Census (LEGA-C; van der Wel et al., 2016) at $z \sim 0.8$ have already demonstrated significant evolution of high-order stellar kinematic parameters (in particular h_4), confirming the importance of galaxy mergers to the evolution of massive galaxies (D'Eugenio et al., 2023a,b). The broad range of environments probed by MAGPI have also been used to show that environment plays a secondary but significant role moderating the internal mass distribution of galaxies at intermediate cosmic times (Derkenne et al., 2023).

Going beyond single parameter indicators of stellar kinematics can help to further isolate the relative importance of internal and external processes, where *in-situ* star formation and mergers/accretion are expected to influence the balance of hot and cold orbits in different ways. Within MAGPI we are using DYnamics, Age, and Metallicity Indicators Tracing Evolution (DYNAMITE; Jethwa et al., 2020) to reconstruct data from the MAGPI MUSE and theory surveys. DYNAMITE is a next-generation implementation of the Schwarzschild orbit superposition method, which uses a weighted library of numerically integrated stellar orbits to reproduce observables such as surface brightness and kinematic moments (for example, v, σ, h_3, h_4).

Figure 3 shows an example of DYNAMITE applied to both MAGPI and EAGLE galaxy data, illustrating its ability to reproduce details of MUSE observations (in this case surface brightness and velocity) even at $z = 0.3$. The value of this analysis is twofold: first, it facilitates an assessment of the orbit reconstruction, and especially its dependence on spatial and spectral resolution, through comparison with the simulated particle data; and second, it allows a direct comparison with observations, such that the orbital distribution in simulations can be used to study the origin of different kinematic components in the data.

Stellar populations

Where kinematics help us to understand details of the assembly process, stellar populations provide a view of when and where stars form. MAGPI spectra are sufficiently deep that they facilitate mapping

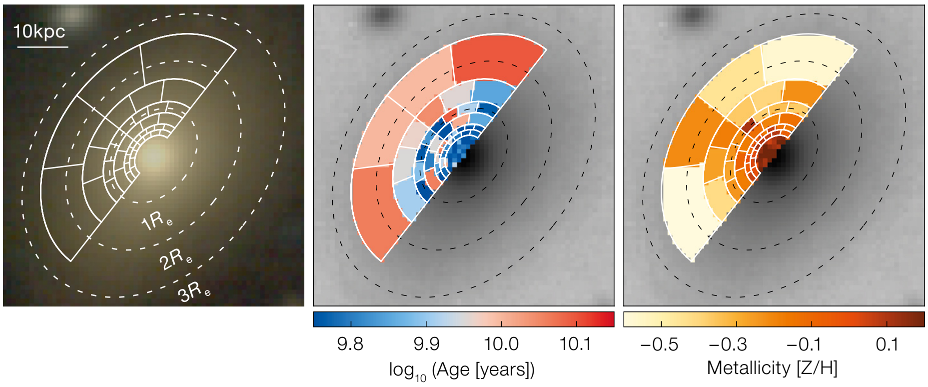

Figure 4. Example stellar population measurements derived for the primary galaxy in MAGPI 1501 (i.e., Figure 1). Left to right, the panels show the mock *gri*-band image, light-weighted stellar age, and light-weighted stellar metallicity in annular and azimuthal bins as indicated. Dotted lines mark 1, 2 and 3 half-light radii (R_e) as indicated. Figure adapted from Mendel et al. (in preparation).

key stellar population parameters such as mean metallicity and mean stellar age out as far as two to three half-light radii when binned. An example for one of the MAGPI central galaxies is shown in Figure 4, where the stellar age and metallicity, [*Z/H*], are traced out to about two half-light radii with individual bins reaching a signal-to-noise in the continuum of more than 20.

The value of these measurements is more clearly illustrated in Figure 5, where we compare MAGPI data against stellar population profiles derived for MaNGA galaxies by Lu et al. (2023). We find that the metallicity gradients derived for MAGPI are entirely consistent with MaNGA galaxies of a similar mass; however the derived age gradients are substantially flatter, particularly in the outskirts. The interpretation of falling age gradients by Lu et al. (2023) is that of an increased contribution from a young stellar disc outside the central bulge region, suggesting that MAGPI galaxies may lack a comparable disc-like component.

Star formation

Despite the majority of MAGPI primary galaxies being relatively gas poor, a number of galaxies across the survey host substantial, extended gas discs whose properties can be used to understand recent gas accretion and the role of environment in modulating star formation activity. Figure 6 shows the distribution of MAGPI galaxies in terms of star formation rate (SFR) and stellar mass, where the sample has been limited to only those objects in the range of $0.25 < z < 0.42$ with robust SFR estimates. This Figure emphasises the power of MAGPI data for studying a broad range of galaxies, where in this case we trace the global SFR–mass relation over about five orders of magnitude in stellar mass.

In addition to these integrated measurements, many star-forming galaxies are resolved by the MAGPI point spread function and can be used to study radial profiles of star formation, in many cases out to two or three effective radii. A detailed comparison of these data with SFR profiles from MaNGA will be presented in Mun et al. (submitted to MNRAS).

The distant Universe

In addition to our primary targets, MAGPI data reveal many background sources which are identified using strong emission and absorption features from the far-UV, for example Lyα to [OII]. The combination

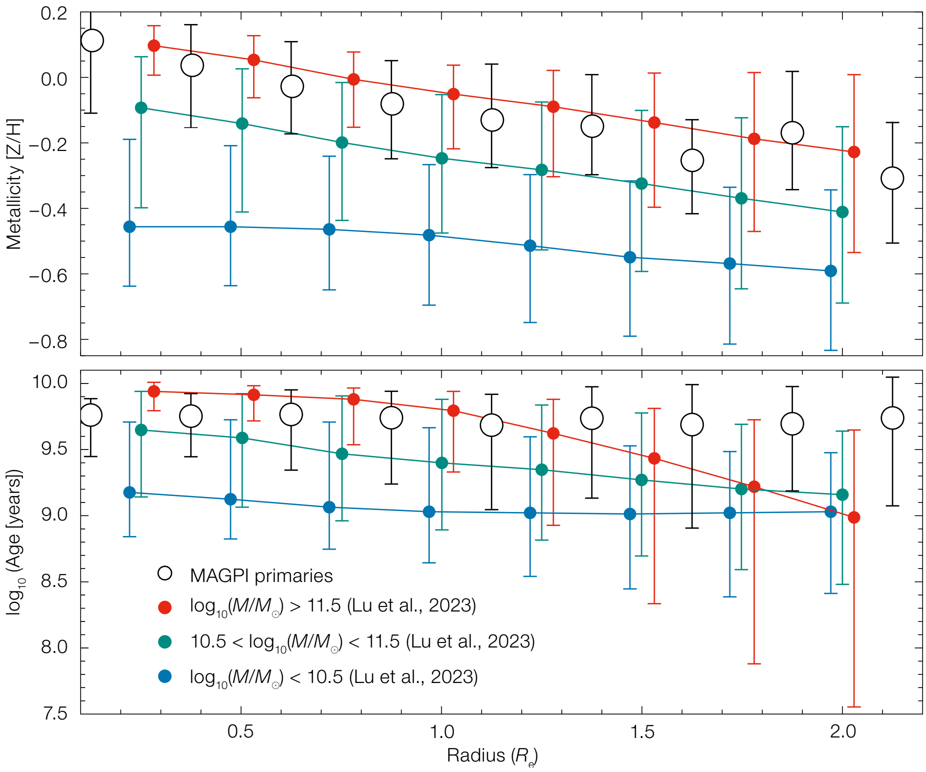

Figure 5. Comparison of metallicity (top) and age (bottom) profiles between MAGPI primary galaxies and comparable galaxies in MaNGA as derived by Lu et al. (2023), demonstrating the large spatial coverage of MAGPI. Figure adapted from Mendel et al. (in preparation).

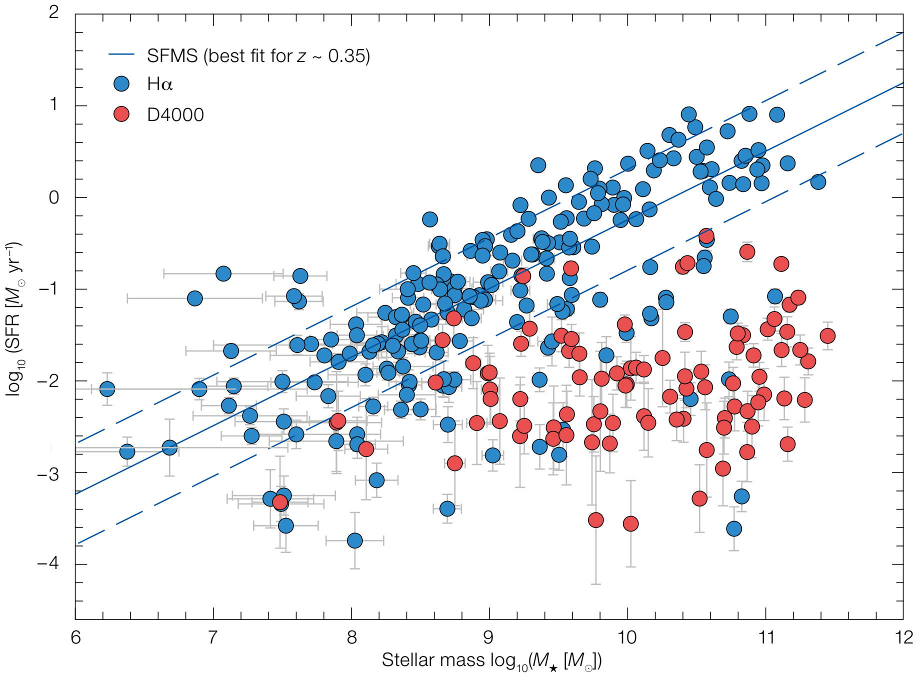

Figure 6. Star Formation Rate (SFR) as a function of stellar mass for current MAGPI fields. The blue line shows a best fit for the star formation main sequence (SFMS) derived from Hα data. This figure is adapted from Mun et al. (submitted to MNRAS).

of wide area (56 arcmin^2) and intermediate exposure time (4 hours) mean MAGPI is ideally suited to the discovery of rare, bright targets compared to other MUSE surveys (for example MUSE deep and MUSE-Wide), with a reduction in cosmic variance due to the spatially disjoint nature of the survey footprint. This has already been realised with the discovery of three rare double-peaked Lyα emitters at $2.9 < z < 4.8$ exhibiting strong blue-peak emission (Mukherjee et al., 2024). Two of these three are extended sources covering areas of 25 × 26 kpc ($z = 2.9$) and 19 × 28 kpc ($z = 3.6$), with the strongest contribution to the blue emission from bright cores associated with the sources. In contrast, the third blue-peak Lyα emitter, at z ~ 4.8, is a compact system and stands as the highest-redshift strong blue-peak emitter ever detected.

Galaxies with strong blue-peak emission are unique systems providing insight into the scattering of Lyα photons by neutral hydrogen. Lyα lines with a stronger blue peak than the red peak usually imply inflows of circumgalactic medium gas along the line of sight during the accretion phase (for example, Ao et al., 2020; Blaizot et al., 2023). In this context, the galaxies discovered in MAGPI suggest inflowing gas systems or edge-on morphologies. Recent cosmological zoom-in simulations (Blaizot et al., 2023) predict < 20% of double-peaked Lyα emitters should have a dominant blue peak, which is consistent with the numbers presented by Mukherjee et al. (2024). These three systems are a part of a larger campaign to catalogue Lyα emitters and absorbers with MAGPI fields — currently 360 new sources across 35 MAGPI fields.

Outlook

MAGPI is a first step towards building large, spatially and spectrally resolved samples of stellar kinematics outside the nearby Universe. Future ESO facilities like the MCAO Assisted Visible Imager and Spectrograph (MAVIS) on the VLT and the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI) on ESO's Extremely Large Telescope will enable us to push such resolved lookback studies even farther, dramatically improving our ability to confront complex cosmological simulations with equally detailed observational constraints.

Combining these resolved stellar and (ionised) gas data with atomic and molecular gas measurements is an obvious next step towards understanding the full baryon cycle in galaxies at these intermediate redshifts. Such observations are already within reach of ALMA and the Northern Extended Millimeter Array (NOEMA), and will be a priority for the Square Kilometre Array (SKA) and SKA pathfinder surveys.

Acknowledgements

We would like to thank the ESO staff on Paranal for their substantial and ongoing support throughout the MAGPI observing programme.

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DOI: 10.18727/0722-6691/5350

X-Shooting ULLYSES: Massive Stars at Low Metallicity

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The Hubble Space Telescope has devoted 500 orbits to observing 250 massive stars with low metallicity in the ultraviolet (UV) range within the framework of the ULLYSES program. The X-Shooting ULLYSES (XShootU) project enhances the legacy value of this UV dataset by providing high-quality optical and near-infrared spectra, which are acquired using the wide-wavelength-coverage X-shooter spectrograph at ESO's Very Large Telescope. XShootU emphasises the importance of combining UV with optical spectra for the consistent determination of key stellar parameters such as effective temperature, surface gravity, luminosity, abundances, and wind characteristics including mass-loss rates as a function of metallicity. Since uncertainties in these parameters have implications across various branches of astrophysics, the data and modelling generated by the XShootU project are poised to significantly advance our understanding of massive stars at low metallicity. This is particularly crucial for confidently interpreting James Webb Space Telescope (JWST) data of the earliest stellar generations, making XShootU a unique resource for comprehending individual spectra of low-metallicity stars.

The role of metallicity

Over the past few decades, it has become clear that metallicity — the relative amount of heavy elements like iron (Fe) — significantly influences the fundamental properties and behaviour of stars. This chemical make-up affects crucial stellar characteristics such as how hot they are and how they pulsate, while in the case of massive stars it also sets the rate of mass loss from their powerful stellar winds, as hot stars are driven by radiation pressure on metallic line opacity. Since the beginning of the Universe, metallicity has been on the rise. This increase is due to the chemical enrichment caused by stellar winds and supernova (SN) explosions. Ultimately, this has led to the metal-rich environment we find in our Milky Way galaxy today, approximately corresponding to the metallicity of our Sun.

But here's the exciting part: it is not just redshift and cosmic time that determine a galaxy's metal content. Another key factor is a galaxy's mass. This means we have a unique opportunity to explore the more pristine conditions similar to the early Universe by studying low-metallicity dwarf galaxies right in our cosmic backyard. In particular, the Small and Large Magellanic Clouds (SMC and LMC), which contain just about 20% and 50% of the heavy elements found in our Sun are ideal laboratories. Exploring these 'metal-poor' galaxies offers us a glimpse of what the Universe was like in its infancy. It is like looking at a cosmic time capsule, telling us the story of the evolving Universe through the lens of stellar metallicity.

The metallicity-dependent fate of massive stars

The Universe still holds many secrets. Of particular relevance to our objectives are the processes governing the formation of black holes (BHs) over time and as a function of metallicity, as well as the physics underlying the occurrence of superluminous supernovae (SLSNe) in low-metallicity environments. Among these mysterious explosions is a subset that might involve an extremely disruptive phenomenon known as a pair-instability SN, where the entire star is obliterated, and which was initially theorised back in the 1960s (Fowler & Hoyle, 1964). However, concrete observations of such events in the real world have so far remained elusive.

Understanding the boundary between BH and pair-instability SNe is paramount for our understanding of gravitational wave (GW) events. While GW events represent just a small fraction of the possible outcomes of stellar evolution, the broader question of whether a massive star ultimately becomes a neutron star, a BH, or experiences a pair-instability SN is of profound significance in our understanding of how the Universe becomes enriched with elements. A single pair-instability SN explosion resulting from a 300-solar-mass progenitor star could contribute more heavy elements than the entire range of stars from a fully sampled initial mass function below it (Langer, 2009).

The ubiquitous property of the most massive stars involves their metallicity-dependent mass loss, which is the key physical process that sets the boundary between BH formation and pair instability (for example, Yusof et al., 2013; Köhler et al., 2015). For this and many other reasons we need to test our theoretical predictions of metallicity-dependent winds against large sets of reliable empirical data (Vink et al., 2023, XShootU I).

The powerful combination of ultraviolet and optical spectroscopy

The ultraviolet (UV) region of the spectrum provides access to a unique suite of stellar wind diagnostics, in particular the P Cygni lines associated with abundant chemical species like C IV (Figure 1). The blue boundary of the P Cygni profile offers a reliable means to gauge the terminal wind velocity (Prinja, Barlow & Howarth, 1990; Hawcroft et al., 2023, XShootU III). However, on its own the UV part of the spectrum presents certain challenges, stemming from uncertainties in the ionisation state which limit the ability to quantify the mass-loss rate in massive stars (Lamers & Leitherer, 1993). The optical range emerges as a critical complement to UV spectra in order to acquire accurate stellar and wind parameters (as depicted in Figure 1; Fullerton et al., 2006; Oskinova, Hamann & Feldmeier, 2007; Puls, Vink & Najarro, 2008).

It is not just the wide wavelength range — from the UV to the optical — that is crucial for building an appropriate framework of metallicity-dependent stellar winds, but also the size of the sample. Historically, most investigations into the winds of massive stars featured limited sample sizes (typically around 10), along with varying coverage across different instruments, wavelength ranges, and analysis tools.

The HST ULLYSES opportunity

Developments in sample size are currently undergoing a revolution, thanks to the HST ULLYSES project. This initiative, a Director's Discretionary Time (DDT) endeavour of 1000 orbits, was conceived by a dedicated working group. The project comprises two distinct parts: a 500-orbit programme focused on young T Tauri stars, and a comparable allocation of HST orbits for the massive star component. The latter aspect of the DDT project received substantial support from the massive star community, including backing from entities like the IAU Commission G2 on Massive Stars. The project encompasses the entire range of spectral types and luminosity classes among OB-type stars within the LMC and SMC regions. This unprecedented coverage includes representatives of all stars with masses exceeding 10 $M_{\odot}$, as indicated in the Hertzsprung–Russell diagrams of the LMC and SMC presented in Figure 2. XShootU also includes a small number of stars in even lower-redshift galaxies.

The dataset generated by this project will leave a lasting legacy, not only enhancing our understanding of stellar winds but also serving as a crucial spectral library from which to construct accurate population synthesis models. Recognising the pivotal role played by the optical wavelength range in determining both stellar and wind parameters, the community strongly advocated that this exceptional opportunity presented by a substantial UV legacy dataset should be complemented by an equally substantial and high-quality dataset in the optical. Hence

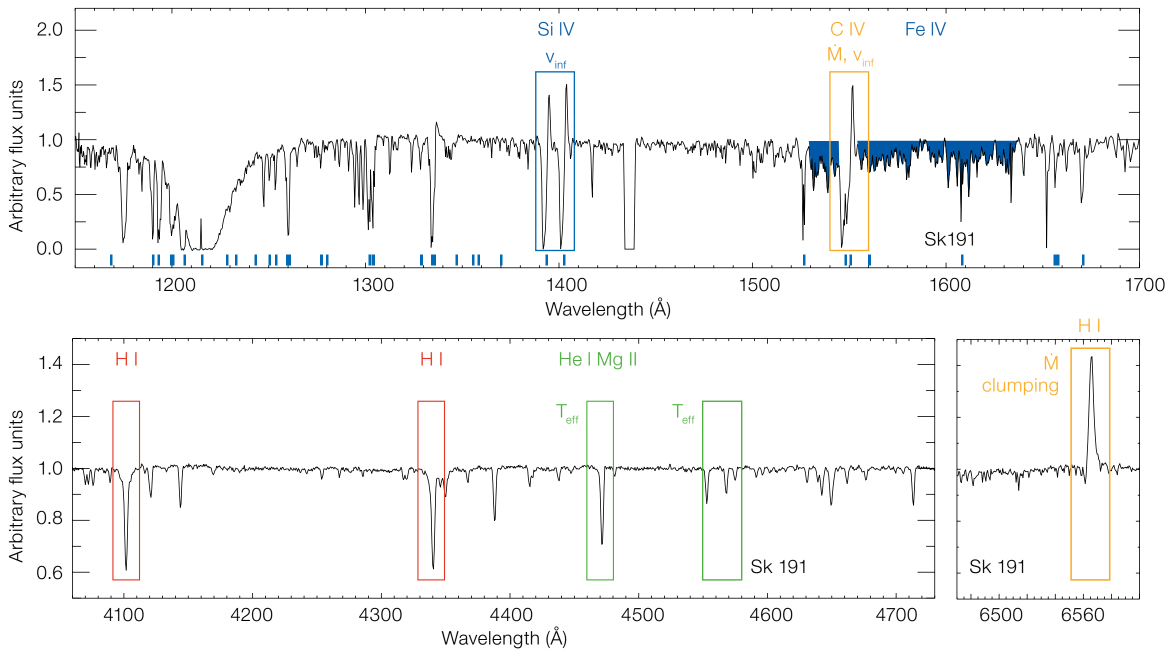

Figure 1. UV (ULLYSES) and optical (XshootU) spectroscopy of the early B supergiant Sk 191 in the SMC, highlighting key photospheric (red and green) and wind (blue, orange) diagnostics.

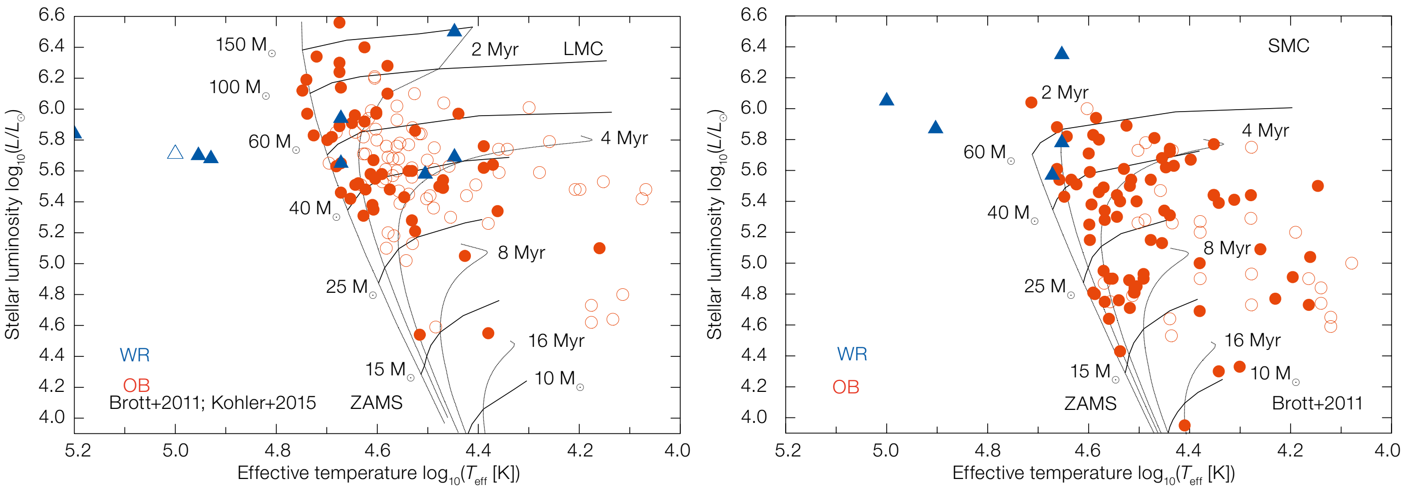

Figure 2. Hertzsprung–Russell diagrams highlighting the location of ULLYSES/XshootU targets (OB: red circles, WR: blue triangles) in the LMC (left) and SMC (right), compared to evolutionary models from Brott et al. (2011) and Köhler et al. (2015).

the inception of the XShooting ULLYSES (XShootU) project[1].

As a bonus, the X-shooter spectrograph offers the additional prospect of establishing a spectral library in the near-infrared. Given that many of the world's newest telescopes have their prime capabilities in this part of the electromagnetic spectrum, it is important that we extend our UV+ optical analysis tools into this regime.

The XShootU advanced data products

Providing advanced data products to the community is one of the main goals of the XShootU collaboration. The optical (UVB+VIS) data have already been reduced and an example of the UVB data is shown in Figure 3. A comprehensive account of these higher-level data products is presented in XShootU's Data Release 1 (Sana et al., 2024, XShootU II), with the data reduction processes for the near-infrared spectra following later.

The raw data first underwent data reduction using the ESO X-shooter pipeline, with a focus on determining response curves. This involved ensuring equal flat-fielding for the scientific targets and flux standard stars, improving the flux standard models. We then processed the pipeline products using our own procedures, generating a range of advanced data products. These included corrections for slit losses, absolute flux calibration, (semi-)automatic rectification to the continuum, and removal of telluric lines. Additionally, the spectra from different epochs were corrected for barycentric motion and combined to create a single, flux-calibrated spectrum covering the entire optical range with the highest possible signal-to-noise ratio.

Our analysis revealed an undocumented recurring ghost artefact present in the raw data. We further introduced an enhanced flat-fielding strategy to minimise artefacts when scientific targets and flux standard stars were observed on different nights. The improved flux standard models and a new set of reference points allowed us to significantly reduce artefacts in the correction of response curves, especially in the wings of the Balmer lines, where discrepancies decreased from a few percent of the continuum level to less than 0.5 percent.

Furthermore, we confirmed the existence of a radial velocity shift of approximately 3.5 km s^{-1} between the UVB and VIS arms of X-shooter and demonstrated the absence of short-term variations affecting radial velocity measurements. We achieved a radial velocity precision of less than 1 km s^{-1} on sharp telluric lines and between 2 and 3 km s^{-1} on data with the highest signal-to-noise ratios.

This post-processing provided three data products for each target: (i) 2D spectra for each exposure before and after instrument response correction; (ii) 1D spectra as initially generated by the X-shooter pipeline, followed by response correction and various processing steps, including absolute flux calibration, telluric line removal, normalisation, and barycentric correction; and (iii) co-added, flux-calibrated, and rectified spectra spanning the full optical range, combining all available XShootU exposures. For the majority of targets, the final signal-to-noise ratio per resolution element exceeds 200 in both UVB and VIS co-added spectra.

Reduced data and the most important advanced data products will be made accessible to the scientific community via the ESO Science Archive Facility in line with ESO's policy for Large Programmes. Together with the HST UV ULLYSES data available for MAST2, they enable a variety of scientific investigations, ranging from detailed studies of stellar atmospheres and stellar winds to the creation of empirical libraries for population synthesis.

The XShootU project

XShootU is a community-focused project, where collaboration is organised through 14 working groups that are open for participation to any scientist. We already held a number of online and in-person meetings to facilitate discussions and collaboration among researchers engaged in the spectroscopic analysis of the XShootU data-sets. The topics range from determining the stellar and wind properties of the sample on a broader scale to addressing specialised issues such as the impact of rotational mixing through abundance studies. The primary spectroscopic analysis tools employed are non-LTE codes that include a stellar outflow in spherical geometry, including CMFGEN (Hillier & Miller, 1998), FASTWIND (Puls et al., 2020), and PoWR (Gräfener et al., 2002), or the plane parallel non-LTE code TLUSTY (Hubeny & Lanz, 1995) for stars lacking strong winds.

Research has demonstrated that the characteristics of structured winds significantly influence empirical calculations of mass-loss rates, thereby shaping our comprehension of stellar evolution. Nevertheless, the extent to which mass loss is influenced by wind clumping remains an open question. Within XShootU, we investigate the impact of clumping on spectral and luminosity classes at various metallicities. The spectral modelling leverages advanced model atmosphere codes, capable of addressing clumping properties with varying degrees of complexity (Sander et al., in preparation).

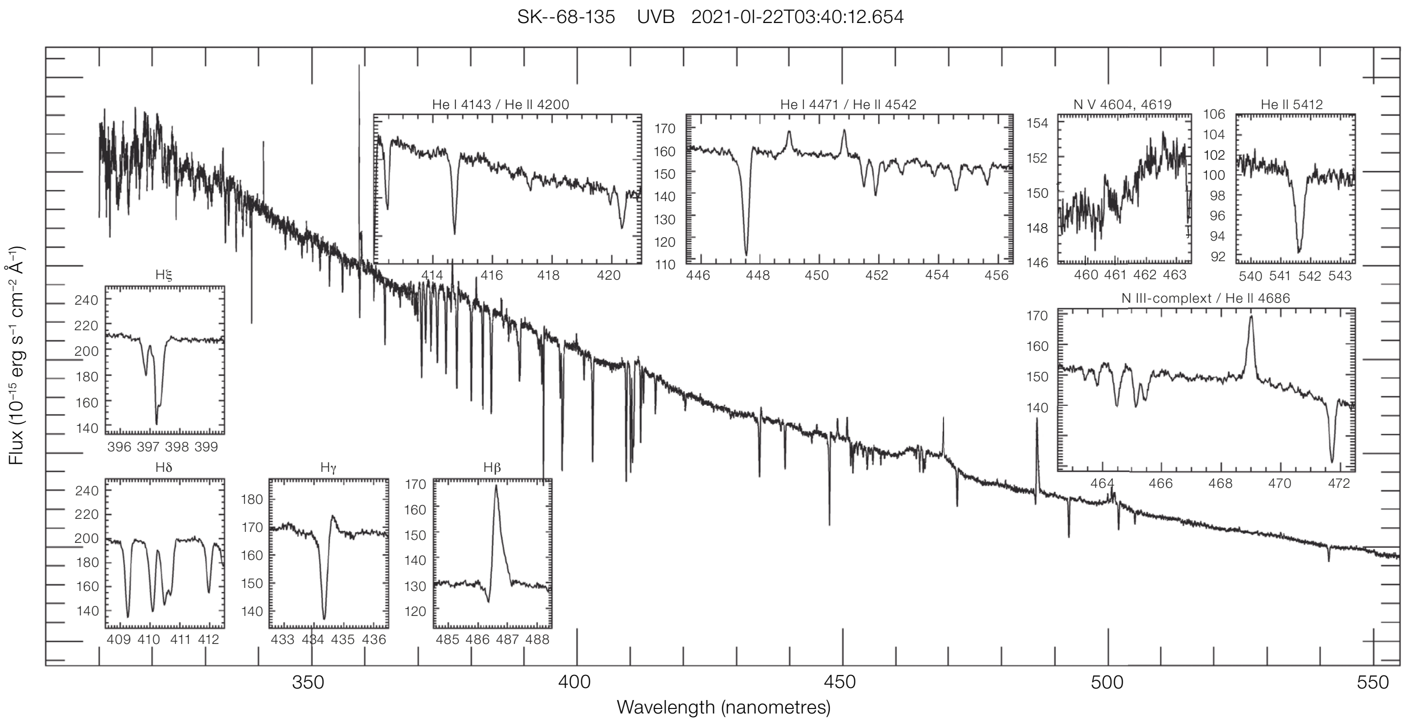

Figure 3. VLT/Xshooter UVB spectroscopy of the late O supergiant Sk –68° 135 in the LMC.

Early spectral synthesis results

Some of the key science goals from XShootU concern the role of metallicity in setting the mass-loss rate from massive stars and how metallicity may affect internal mixing. In order to achieve these objectives we require the determination of mass-loss rates as well as abundances in both the UV and the optical.

An early study into interior mixing was performed by Martins et al. (submitted to A&A) using the CMFGEN code. Figure 4 shows nitrogen (N) abundances versus the surface gravity (g) of O6.5–O9 dwarfs in the different environments of the SMC, the LMC, and the Milky Way. Surface gravity serves as a proxy for evolutionary time, while the surface N enhancement on the y-axis takes on the role of rotational mixing efficiency. The Figure shows that N enhancement occurs earlier in the main sequence evolution (i.e., at higher log *g*) in the SMC than at higher metallicity. These early results appear to support rotational mixing which is theoretically expected to be more efficient at lower metallicity.

Regarding wind properties, Figure 5 shows the mass-loss rate of LMC and SMC supergiants studied by, respectively, Brands et al. (in preparation) and Backs et al. (in preparation) using a genetic algorithm method and the fastwind code. The results indicate that the mass loss versus luminosity relation becomes steeper in lower metallicity environments than at higher metallicity.

These early results are based on the analysis of relatively modest subsets of the XShootU data. More definitive answers will be obtained over the next few years as analyses of the full sample are completed. We expect that even basic stellar parameters such as stellar mass may need to be re-evaluated in comparison to the pre-ULLYSES era. For instance, Pauli et al. (2022) studied the earliest type eclipsing binary in the SMC, leading to a significant revision of its component masses.

Spectral libraries and the more distant Universe

Stellar spectral libraries play a fundamental role in stellar population synthesis models, which are essential tools for studying the fundamental properties of unresolved stellar systems. Multiple empirical stellar spectral libraries, each

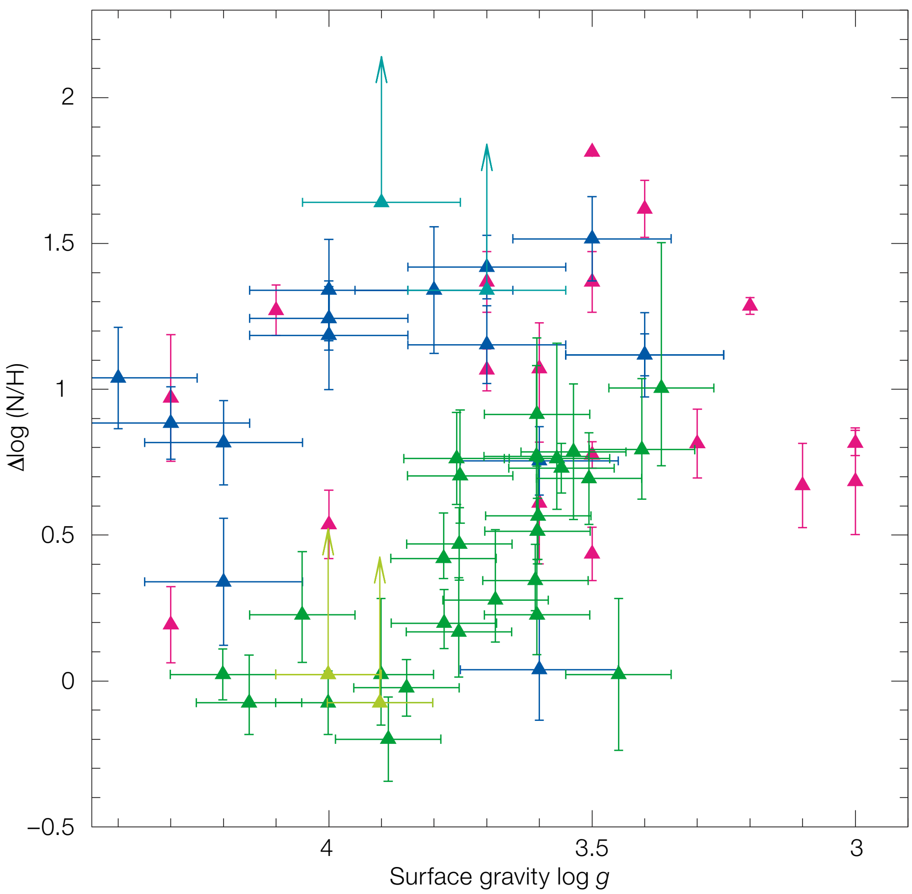

Figure 4. Logarithm of N/H minus the baseline value as a function of surface gravity for SMC/LMC/MW stars in blue/magenta/green. The light green colour is for upper or lower limits in the Galaxy, pink is for the LMC. Note that N-enrichment appears earlier in the main sequence (at higher log *g*) for the lower-*Z* environment of the SMC than in the LMC/MW. From Martins et al. (submitted to A&A).

gathered with distinct objectives, are publicly accessible. One significant limitation of the existing empirical libraries today is their coverage of hot and young stars at low metallicities.

In terms of spectral resolving power, only the X-shooter Spectral Library (XSL; Verro et al., 2022) and ELODIE archive (Moultaka et al., 2004) complement the X-Shooting ULLYSES dataset. XShootU represents the most comprehensive, highest-signal-to-noise ratio, and highest-resolution library of hot, massive stars, encompassing the broadest spectral range. Although numerous libraries cater to low-mass stars, they exhibit gaps in coverage for high-mass stars.

As an illustration, we compare the XShootU target sample with the XSL library (Verro et al., 2022), which was specifically designed for stellar population synthesis. In Figure 6, we display the Hertzsprung–Russell diagram coverage of the XSL library, revealing the absence of massive OB stars at any metallicity. XShootU excellently complements the missing parameter space of the XSL library. In tandem, these two libraries enable self-consistent population synthesis models for systems containing both young and old stars. Population synthesis models fall into two categories: semi-empirical models where the stellar evolution tracks are theoretical, but the individual stellar spectra are observed, and fully theoretical models where both components are calculated. XShootU will lead to enhancements in semi-empirical models by providing the most comprehensive spectral library of massive stars to date. Furthermore, XShootU will guide the development of new generations of atmosphere and evolution models, contributing to the refinement of fully theoretical population synthesis models.

XShootU will also provide an upgrade to the current Starburst99 (Leitherer et al., 1999) LMC + SMC library, significantly enhancing the realism of population synthesis predictions. Once this library is incorporated into Starburst99 and other population synthesis models, corresponding Cloudy photoionisation models (Ferland et al., 2017) will be computed to consider the contributions of ionised gas and dust to the integrated light of young OB star populations. These models will be made publicly available.

Future outlook

In summary, it is anticipated that the XShootU project will furnish a wealth of data, models, and novel insights into massive stars in low-metallicity environments. It is crucial to emphasise that the overarching objective of XShootU is to establish a high-quality, consistent optical database that complements HST ULLYSES.
The resulting legacy datasets hold significant importance in ensuring the accurate interpretation of unresolved observations obtained with the JWST (Curti et al., 2023; Carnall et al., 2023). The project's subsequent aim is to deliver consistently determined stellar and wind parameters

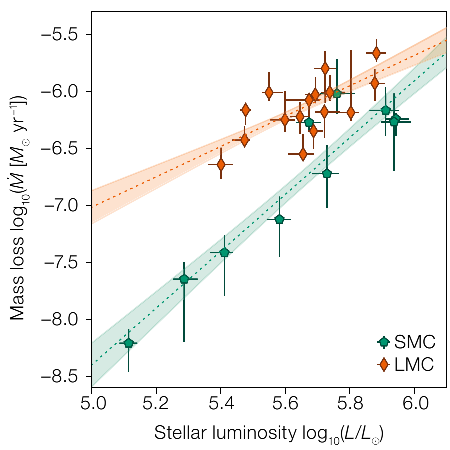

Figure 5. The empirical mass-loss luminosity relation for XShootU stars in the LMC (Brands et al., in preparation) and the SMC (Backs et al., in preparation). Note the steeper mass-loss/luminosity dependence in the SMC.

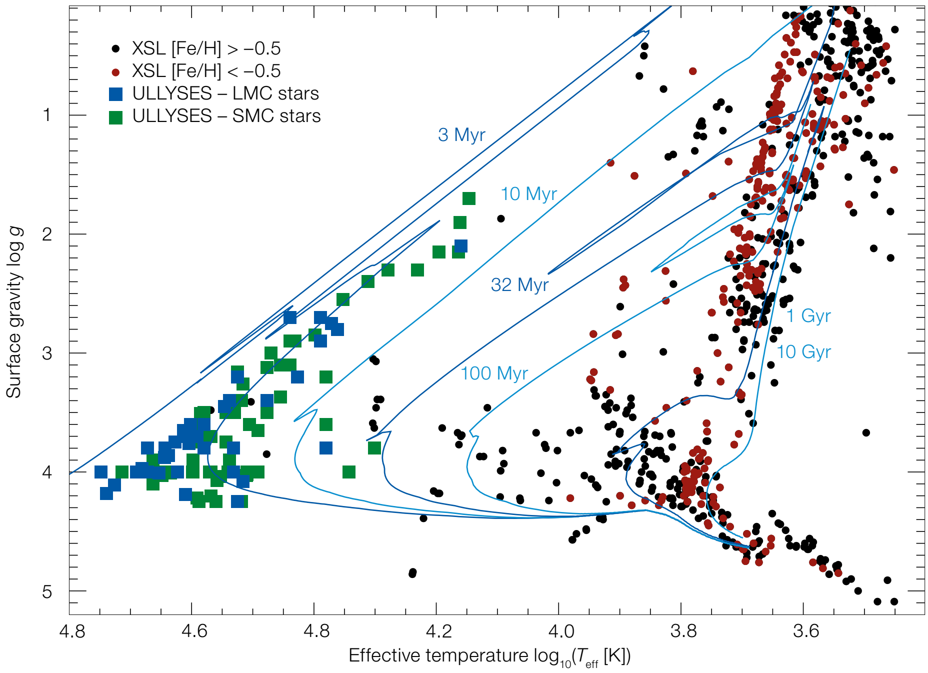

Figure 6. Comparison between temperatures and gravities of metal-poor and metal-rich stars in the XSL spectral library (Verro et al., 2022) and ULLYSES targets in the LMC (blue) and SMC (green).

through the integration of UV and optical datasets. This phase of the of the project will not only incorporate state-of-the art non-LTE physics, but will also rigorously assess the various spectral synthesis codes and analytical methods.

Some of the analysis is already in progress. However, there is plenty of room for new participants to become part of this project. Additionally, the X-shooter data are accessible to the community, and we also intend to make the higher-level data products available to the broader scientific community. The high-quality XShootU data will have long-term value for a wide range of research projects, including many which may not even have been envisioned yet.

Acknowledgements

We warmly thank the data reduction team (WG2) lead by Hugues Sana and Frank Tramper from KU Leuven for post-processing the spectra to enable quicker analysis. We also acknowledge Andrea Mehner from ESO for her help in the preparation of the OBs, and Sarah Brands and Frank Backs from the University of Amsterdam for sharing early results presented in Figure 5 on mass-loss rates versus luminosity.

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Links

[1] XShootU webpage: https://massivestars.org/xshootu/
[2] Ullyses data website: https://ullyses.stsci.edu/ullyses-download.html

ESO/Juan Carlos Muñoz Mateos

The four Auxiliary Telescopes at ESO's Paranal Observatory can be seen gazing up at the night sky in this picture. With dark and pristine skies, Paranal is one of the best places on Earth to study the Universe from. As seen in this spectacular image, the view is really full to the brim of exciting things to look at.

Telescopes and Instrumentation

ESO/A. Ghizzi Panizza (www.albertoghizzipanizza.com)

This image shows the stunning night sky over the Swedish–ESO Submillimetre Telescope (SEST) telescope at ESO's La Silla Observatory in Chile. Until its retirement in 2003, SEST used its 15-metre main dish to observe the cold gas clouds where stars form. Now the telescope, perched at 2375 metres altitude, watches silently over the landscape of the Atacama Desert.

DOI: 10.18727/0722-6691/5351

Paranal Instrumentation Plan Lessons Learned 2023

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The 2023 Paranal Instrumentation Programme Lessons Learned exercise assessed the recent major projects delivered to Paranal. The goal was to identify good practices and improvements for the future by examining cost, schedule, and performance against targets. The review also considered ESO's response to the previous exercise and lessons learned from interactions with partner institutes in Europe. This article summarises the overall findings and key recommendations for ESO.

Introduction

The 2023 Paranal Instrumentation Programme (PIP) Lessons Learned exercise was scoped by ESO as a review of the lessons learned for the future from the major projects delivered recently to Paranal, namely the GRAVITY instrument, the Multi-AperTure mid-Infrared SpectroScopic Experiment (MATISSE), the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO), the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES+), the Adaptive Optics Facility (AOF) and the Very Large Telescope Interferometer (VLTI). Instruments still under construction will be covered in a future exercise. The goal of the exercise was to explore the lessons learned to identify good practice and improvements for the future. Specifically, the panel was tasked with:

- examining the overall cost, schedule, and performance of each project against its targets;
- reviewing and commenting on the response by ESO to the last exercise; and
- examining the lessons learned in interacting and partner institutes in Europe.

In this article we present the overall findings of the 2023 Lessons Learned review and the key recommendations made to ESO, including some suggestions for potential actions. The review panel consisted of Matthew Colless (Chair), Michele Cirasuolo (Vice-chair), Anja C. Andersen (La Silla Paranal Committee), Vanessa Hill (Scientific Technical Committee), Rebecca Bernstein and John Monnier (external members), Sebastian Egner (internal member) and Antoine Mérand (secretary).

Overall lessons learned

The lessons learned summarised below are the consensus conclusions drawn by the panel from information provided in the course of the review (the documentation and presentations provided by the representatives of the consortia, the ESO-Garching follow-up teams, and the ESO-Paranal operations teams) together with the subsequent discussions.

Previous lessons learned

The timeframe covered by the projects in this review is important, given that a goal of this Lessons Learned exercise is to "review and comment on the response by ESO to the last exercise". All these projects started prior to the previous review (see Figure 1), and so only benefitted from any changes that ESO implemented in response during the latter stages of each project. This makes it difficult to judge the effectiveness of ESO's response to the previous exercise based on these particular instruments and facilities.

It is therefore not surprising that many issues noted in the previous exercise were also apparent in these projects. On the other hand, some positive changes were seen, most notably in improved relations between the ESO-Paranal operations teams and the consortia and ESO-Garching follow-up teams during the very intense commissioning phases of these instruments and facilities, which generally occurred after the previous Lessons Learned exercise.

Infrastructure implications

One of the notable features of the instruments/facilities covered by this Lessons Learned review is that they mostly involve

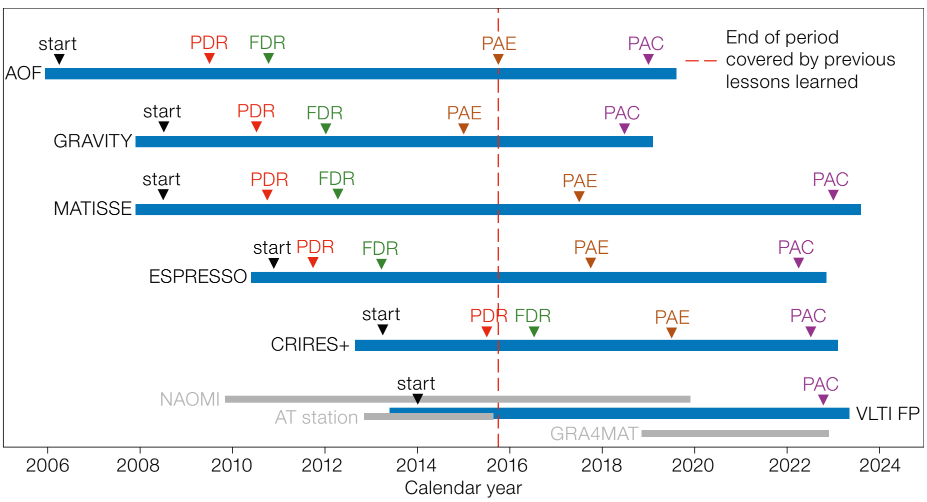

Figure 1. Timelines of instrument/facility projects covered by this review, showing key milestones for each project and the previous Lessons Learned exercise (red dashed line). 'Start' means the beginning of the project at ESO (i.e., after phase A); PDR = Preliminary Design Review; FDR = Final Design Review; PAE = Preliminary Acceptance Europe; and PAC = Preliminary Acceptance Chile.

substantial coordination with (or major upgrades to) the infrastructure of the VLT/I facility and its operations. This contrasts with most instruments covered in previous reviews, which tended to have (relatively) simpler interfaces to the telescopes and their infrastructure. It was clear that the degree of coordination with existing infrastructure was underappreciated in the initial stages of these projects and consequently projects were inadequately scoped and costed; this was broadly true for both ESO-led projects and consortia-led projects.

Overview of cost and schedule

Depending on the project, the hardware cost was provided by some combination of ESO and consortia, and the latter were compensated with nights of guaranteed time observations (GTO). While for GRAVITY and MATISSE the consortia contributed most of the hardware cost, for ESPRESSO and CRIRES+ the contributions were more balanced between ESO and the consortia. The costs of the VLTI and AOF facilities were covered almost entirely by ESO.

In terms of effort (FTE = person-years) used for the projects, there is no traceability nor visibility of the FTEs spent by the consortia, but only those spent by ESO for the follow-up team and the specific work packages delivered by ESO, such as detectors. For the VLTI and the AOF the FTEs also account for all the work done in-house at ESO, to upgrade infrastructure and to deliver the project. Comparing the planned FTEs at kick-off to the actual FTEs spent, the ESO effort over-run ranged from a factor of 1.3 to 2.9, with a mean of 1.9.

For estimating the delays to schedule (planned versus actual), the time from kick-off to Preliminary Acceptance Europe (PAE) is considered the fairest and most reliable measure of project duration. The schedule over-run in reaching PAE is similar for the various projects, ranging from a factor of 1.3 to 2.5, with a mean of 1.8. For all projects, most of the delays happen in the manufacturing, assembly and integration (MAIT) phase, between Final Design Review and PAE.

Integration of project teams

The consortia, ESO-Garching and ESO-Paranal teams for almost all the projects reviewed here reported benefits from better project integration as a result of members of each of these teams embedding/visiting/interacting more with the other teams on the same project. Specific examples from the ESPRESSO and AOF projects were given, where these benefits were clearly realised and positively recognised by all parties. But these actions were taken in response to crises, while it seems likely that increased interactivity would help to avert not only crises but also some of the misunderstandings and errors in instrument design or implementation that appeared in most of these projects during commissioning or in operation. Benefits were felt to be greatest when interactions occurred earlier and over longer timescales; leaving interactions until a formal review was as likely to cause problems as to solve them. All the externally led projects indicated they would have appreciated better integration with ESO and a more continuous contribution of ESO technical experts so as to bring in experience and to communicate and ensure the implementation of ESO standards (rather than just checking their compliance at the reviews).

There was a call on all sides for more engagement by the ESO-Paranal operations team in earlier phases of instrument development, as expressed by the consortia, by the ESO-Garching follow-up teams, and by the ESO-Paranal operations team. This engagement should be over the life of the project and not just at reviews, although there is real value in having active Paranal involvement in reviews if this can provide some assurance to the consortia and ESO-Garching teams that design decisions are in some sense approved by Paranal. Engagement needs to be through interaction of personnel as well as through formal procedures and documentation. Several groups mentioned problems and delays with the change control process at Paranal.

On the other hand, increased engagement was a real concern for Paranal operations team members and management, who did not feel they had sufficient capacity to supply effort to support instrument projects prior to commissioning because existing resources were wholly consumed by the demands of operations. The review panel could clearly see this tension and the strains imposed on operations staff by such ‘additional’ workload. Nonetheless, the panel considered there to be a plausible case that extra time spent by ESO-Paranal staff on instrument development (if intelligently directed) could potentially reduce the amount of time spent on instrument commissioning, ‘Paranalisation’, maintenance and repairs, leading to a reduced overall load on consortia, on ESO-Garching follow-up teams, and on ESO-Paranal operations staff themselves. To make the handover and operation of the instrument to LPO smoother, a more systematic transfer of the knowledge gained about the behaviour of the instrument during MAIT could be useful. This would include engineering data such as logbooks, solutions to encountered problems, and sensor readings.

Similarly, it was noted that the best outcomes for ESO and the user community were obtained when the teams were constructively engaged well after Preliminary Acceptance Chile (PAC), and there were positive examples of that amongst the instruments/facilities reviewed here. Effective management and good relations with the consortia during the instrument support phase after delivery and the GTO period, together with continuing access to the ESO follow-up team, are the critical ingredients. It was particularly mentioned that it is necessary to update the data-reduction software based on commissioning results and the feedback by users after early open observations with the instrument, and to include revised and improved algorithms. To further optimise the outcome, a more flexible scheme for GTO, perhaps allocating half-nights where appropriate and providing compensating time for bad weather, might be beneficial.

Reviews and documentation

As expected, reviews were a recurring theme. The Lessons Learned panel heard sufficient concerns from all parties to justify the planned ESO ‘review of reviews’.

While the panel will leave specific recommendations to that process, we can report the key concerns expressed by those involved in the projects reviewed here. These included: excessive documentation that was not in fact much used or much use; reviews of instruments being used to drive wider political agendas within ESO; related to that, insufficient independence of the review panels from ESO, especially where ESO was itself a significant element of the project; and insufficient expertise on the review panels, so they degenerate into tick-the-box checks of low-level requirements, rather than incisive investigations into whether instruments meet top-level science requirements effectively and efficiently, and their long term operability. The consortium representatives for one project suggested that the top-level requirements should be the sole focus of reviews at all review stages. The panel was not convinced by that suggestion, believing that reviews need to work down the chain of requirements as the project advances. However, reviews must always keep a close eye on the top-level requirements (particularly the top-level science requirements) and not get hung up on lower-level technical requirements if they do not have significant implications for the top-level requirements. The opinion of most of the consortia (and even of some ESO staff involved in the projects) is that the pendulum may have swung towards micro-management and even 'micro-design', the imposition by ESO of specific design solutions based on taste rather than clear benefits to the top-level requirements, operability, or maintainability. This seems to be due in part to the complexity of the projects (particularly projects with a complicated infrastructure interface), which makes it harder to have a top-level view, and in part to increasing formalisation of the contractual relationship (see below).

Several consortia, ESO-Garching follow-up teams and ESO-Paranal staff recognised the importance of adequate testing in Europe prior to PAE and shipping to Chile, since fixing problems at Paranal is generally (though not invariably) much more complex and expensive.

Communication

As is almost always the case in large, complicated organisations and projects, a common complaint was a failure to communicate information in a clear and timely fashion to all relevant parties within a project. In most cases, this could be put down to a failure (on all sides) to follow the policies and procedures already in place. However, there was also an apparent lack of communication about broader, context-setting information (for example, that GRAVITY was prioritised over other projects, or that the Paranal operations team would have more constrained resources). Such information, if appropriately shared, can be used by all parties to make more realistic plans and can also reduce misunderstanding based on differing assumptions or knowledge. More generally still, the panel recognised that future instrument Principal Investigators, Project Managers and others in key roles (both external and internal to ESO) could potentially benefit greatly from exposure to the information and accumulated knowledge on display in this review that is held by past PIs/PMs and the highly experienced ESO staff at both Garching and Paranal.

Contractual relations

Another broad issue, raised in various forms by most of the projects, is that of contractual relations between ESO and external consortia and the non-contractual relations between different parts of ESO itself. There was a repeatedly expressed desire for the relationship between ESO and the consortia to be more collaborative and less contractual. The consortia reported an increased formalisation of the client-contractor relationship by ESO, with a tendency for this to lead to more adversarial interactions. Obviously, there is a tension between the desire of all parties to have a more effective collaborative partnership and the need for ESO (and sometimes the consortia!) to have a more formal and explicit statement of responsibilities. This is further complicated when (as in most of the projects reviewed here) ESO is delivering significant components of the instrument or facility, and so is simultaneously in a client-contractor relationship and a collaborative partnership. These unavoidable issues are exacerbated when ESO, as internal contractor as well as client, does not live up to the standards it demands of external contractors; there were sufficient examples of this amongst these projects to make this a real grievance for some of the consortia.

VLTI strategy

The VLTI was a focus for three of the six instruments reviewed here (GRAVITY, MATISSE and the VLTI facility itself). ESO's goals of recovering from the slow start of the VLTI and fully exploiting a capability that will remain world-leading even in the Extremely Large Telescope (ELT) era were clearly on display. The enormous scientific impact of GRAVITY and the more modest but still successful applications of MATISSE demonstrate that ESO is turning the corner with the VLTI, making it more scientifically productive and more interesting and usable by a wider (though still specialist) community. Set against this, however, the ESO people most involved still perceive the VLTI to be substantially under-appreciated internally, despite the high priority given to GRAVITY (and now GRAVITY+). There appear to be a few reasons for this perception, including a long-standing bias against the VLTI (considered an unwished-for encumbrance by earlier generations of ESO staff), the failure and cancellation of the Phase-Referenced Imaging and Microarcsecond Astrometry (PRIMA) project, and — more currently — issues with the way that ESO is (or appears to be) outsourcing the VLTI increasingly to some institutes. Some of the ESO staff working on the VLTI feel disenfranchised by the degree of control exercised by the Max Planck Institute for Extraterrestrial Physics (MPE) first in GRAVITY and now in GRAVITY+, which does appear greater than that found in other VLT/I (or ELT) projects. While it was clearly appreciated that without MPE neither GRAVITY nor GRAVITY+ could be realised, there was nonetheless a desire for ESO to maintain some control and engagement, at least at the same level as for other instrument projects. There is the distinct possibility that ESO will lose its most capable people in this field if it does not invest more and exercise more control over VLTI development.

Technology standards

There are clear benefits to having standards in instrumentation technology, software architecture and so on, and these benefits accrue both to ESO and to the consortia in a variety of ways. The two main challenges are: (i) balancing standardisation with quick uptake of powerful new technologies (when is standardisation appropriate in rapidly evolving areas?); and (ii) not imposing standards on projects so late in their development that this has a substantial impact on project cost and schedule (what should the policy be in this regard?). With software standards in particular, there seems to be an opportunity for ESO to provide considerable efficiency savings to consortia by supplying its in-house expertise (see below). There was a widespread view that ESO should also invest more in developing innovative technologies (either in-house or via external contracts) that could be useful or transformative for multiple instruments (for example, gratings, real-time computing, detector controllers, curved detectors, etc.).

In-house capabilities

ESO's instrumentation programmes have benefitted from considerable in-house capabilities and expertise. In earlier times this was generated naturally, because ESO was playing a leading role in a range of instrument projects. Now, however, the instrumentation programme is larger and broader, while in-house capabilities are focussed on the challenge of building the ELT and are constrained by tighter financial circumstances. This means ESO is finding it more difficult to maintain the breadth of expertise needed to be a well-informed client/manager of the instrument programme while simultaneously nurturing the deep expertise in key fields that has been crucial to solving major problems that have arisen within instrument projects. The external consortia emphasised that successful instruments required motivated, competent, and experienced ESO staff with strong technical skills and field experience, who were essential to a productive relationship between the consortia and ESO based on mutual respect. ESO will only have a pool of such staff if it keeps developing at least one instrument (or equivalent) in-house at any time. This might also be partially addressed by embedding some ESO staff in external instrument consortia, but that does not necessarily foster deep expertise in leading instrument projects or critical skills/technologies. Another partial solution may be to delegate some areas of expertise to ESO's closest industry partners. While a lack of in-house expertise has not unequivocally led to issues in the set of instruments and facilities reviewed here, both consortia and ESO participants flagged this as a serious problem that is likely to grow as key experts retire. Moreover, ESO's VLTI experts indicated that key competencies in that area could be lost unless ESO is able to take a greater and more leading role in future VLTI projects. The significant number of retirements of senior managers and technical staff from the 'VLT generation' over the next few years is an added challenge that should be taken as an opportunity for renewal. ESO will need to find ways to attract junior staff and graduate students who are willing and able to be involved in instrumentation projects (both on the science and engineering sides).

Conflict management

Both ESO staff and consortia raised the issue of improving ESO's conflict management skills and procedures in light of the perceived increase in friction between ESO and consortia. Suggestions included: closer, earlier, and more intimate integration of ESO staff with consortia (as discussed above) to make them collaborators and to avoid ESO's just being seen as the 'review police'; better training for ESO staff in managing conflicts; and more rapid escalation of problems to appropriate management levels before they cause damage.

Short-term hirings

The benefits and difficulties of short-term hirings were raised by some of the project teams. Given the unpredictable demand for staff resulting from the uncertainties associated with multiple simultaneous projects, there are clearly potential benefits to ESO if it can access skilled technical staff on a short-term, temporary basis when needed. The panel understands that legal restrictions, and perhaps internal concerns, have made such short-term hirings difficult or impossible, removing an important and effective lever from ESO's toolbox for managing the demands of its instrumentation programme.

Fragmentation and churn

Two other staffing issues raised in multiple contexts were the impact of fragmentation (the slicing of effort into smaller and smaller units) and churn (the rapid turnover of staff). Fragmentation is common in matrix-managed organisations. In theory it appears to be the efficient use of resources, but in practice it is highly inefficient because it atomises attention and imposes overheads, leading to staff stress and low morale. The VLTI facility supplied the clearest example of the cost to ESO of an overly fragmented technical workforce, but other projects also raised the issue. Churn can have various origins but is often a sign of lack of job satisfaction or precarity of employment. It too is highly inefficient, for similar reasons to fragmentation — personnel changes waste accumulated knowledge and impose overheads in the form of retraining requirements and re-establishing relationships. The seven project scientists involved in the CRIRES+ project supply the prime example of churn in this review, but there were other examples.

Finally, there were concerns that ESO staffing requirements were being underestimated because people were (either of their own accord or by direction) only requesting roughly the number of FTEs available, rather than the number of FTEs they really needed. For ESO to understand its true resourcing situation, it is essential that the real FTEs needed for each project are accurately estimated and recorded, reflecting the actual project needs and not just what it is reasonable to request given the constraints of available resources. The panel recognised that a modest level of over-requests (for example, 10–20%) above the available FTEs should be considered normal and appropriate for a large, matrix-managed organisation like ESO, but higher levels indicate over-commitment and signal workload stress. It was also noted that the requests for key experts must be managed carefully to avoid overloading specific individuals.

Software pipelines

The consortia provide data reduction pipeline software for their instruments, which ESO then maintains over the instrument lifetime. In some cases this pipeline software is sufficient for the needs of most users; in others, particularly where the full reduction and analysis are complex and delicate, the pipeline is suitable for basic reduction of the data, but not adequate for full scientific analysis. Some of these issues are considered to be due to a lack of integration of the pipeline development group with the rest of the project team. In some cases, instrument teams have developed their own alternative pipeline software (or valuable add-ons) that are not supported by ESO or available to other users. The panel believes there may be opportunities for ESO to negotiate access to such valuable resources for its user community without owning, paying for, or guaranteeing the software.

Several consortia mentioned that ESO's standard programming language (CPL) is not appropriate anymore, and that it also impedes software development because it is hard to find programmers for it and it excludes the use of software developed in the community (mostly Python-based).

Remote access

The Garching Remote Access Facility (G-RAF) has already proved its value by allowing instruments to be commissioned and operated remotely and should be integrated into future instrumentation project plans (although clearly some things can be efficiently accomplished remotely while others really require hands-on access). More broadly, however, ESO appears to lag behind other leading observatories in providing remote access and observing capabilities. Although the panel understands some of the reasons for this (large and complex facilities with a wide user base, plus cyber-security concerns), we believe that improved remote access capabilities (including solutions for logistics issues and responsibilities) will allow ESO to provide more flexible services to observers and instrument teams, and to save money on operations and maintenance, while reducing climate impact due to air travel.

Future projects

The panel believes there are lessons to be learned from the experiences of the projects reviewed here in relation to selecting, timing, and managing future projects. None of these lessons is new or surprising, and ESO is well aware of all these issues — nonetheless, they are worth emphasising:

- All projects must have clearly specified science drivers, even those primarily providing technology or infrastructure. Project leaders need to regularly re-evaluate their plans in light of the scientific returns, which can be positively or negatively affected by changes in technology, schedule, and external circumstances.
- There is a necessary and healthy tension between the desire to start new projects and the need to finish existing projects to free resources. With both a burgeoning ELT programme and an increasingly constrained financial environment, ESO needs to manage community expectations and new project starts even more carefully: a new project should only start when ESO is reasonably assured it has the necessary resources to support the project over its lifetime.
- ESO also needs to be willing to make hard decisions to cut projects that are failing, that are overtaken by competitors, or that for any other reason are no longer able to deliver value for money to the ESO community. Such hard decisions need to be made as quickly as possible, to minimise pain and maximise gain.
- Given the lengthening timescales and greater resources demanded by innovative instrumentation projects, ESO needs to find ways to encourage the community to initiate visionary concepts while ensuring that only the best, most valuable, projects are accepted for adoption by ESO when it has the resources available to deliver them.
- While ground-based astronomy instrumentation is easier in several respects than space-based instrumentation, in terms of timescale, cost and complexity there is increasing convergence. Consequently, there may be lessons ESO can usefully learn from the competitive approaches used by ESA and NASA for managing their programmes.
- The AOF and VLTI facility projects provide lessons on the advantages and challenges of structuring groups of related smaller projects into overarching larger projects. The main lesson is that applying such structure early can be extremely valuable, particularly for infrastructure-related projects with complex dependencies that may be able to run in parallel or may require careful staging.

PIP resourcing

ESO has many instrumentation programmes, with separate management and budget lines. At present, the PIP is independent of the programmes for ELT first-generation instruments, subsequent ELT instruments, and Technology Development. Given that ESO's strategic plan requires the VLT/I to be maintained as a cutting-edge facility into the ELT era, it is essential that the PIP is sufficiently well resourced to achieve that goal. At present the nominal cap on the PIP is 26.5 FTE and ~ 3.8 million euros (2023) per year capital, which (based on ESO's experience and estimates of the required resources) is intended to allow one new instrument project to be started (or come online) every 1–1.5 years. As there are 13 VLT foci plus the VLTI (16 instruments in all) this would imply that the PIP can replace the full Paranal instrument suite every 16–24 years, which is consistent with the effective scientific lifetimes of 15 to 30+ years for VLT instruments. However, the increasing costs, staff effort, and development times for new instruments are concerns. The delays and extra effort evidenced in the analysis of the recent VLT/I instrument projects strongly suggest that the actual (as opposed to budgeted) ESO staff effort required to support delivery of a new instrument every 1–1.5 years is already at, or beyond, the limit set by the currently available ESO staff effort for the PIP. One way of seeing this is to note that the four consortia-led projects (i.e., setting aside the much more effort-intensive ESO-led projects) required a total ESO staff effort corresponding to six years of the nominal PIP budget. Moreover, the average time to reach PAE for these projects was 6.7 years, with PAC and a science-ready instrument taking significantly longer. The key lesson learned is that, to achieve its stated goal of maintaining a full and competitive instrumentation suite on the VLT/I, ESO will need to become significantly more efficient in the support it provides for future VLT/I instruments and significantly increase the staff effort committed to the PIP, or (more likely) some combination of both.

Given the challenges of completing the ELT and its first-generation instruments, compounded by the tightening of the wider financial environment, it seems likely that the PIP will come under even greater pressure in future. ESO will clearly have some difficult decisions to make regarding future VLT/I instruments, but the panel strongly believes that adequate investment in the PIP is crucial to ESO's long-term scientific impact.

Recommendations and Suggestions

The following key recommendations from the review panel to ESO are goals for follow-up actions that the panel believes would help realise benefits from the lessons learned in this review and previous exercises. In some cases, we also offer suggestions (distinguished by being in italics) for potential ways of implementing these recommendations. Related recommendations are grouped by topic, but the order is not significant.

Infrastructure implications

1. ESO should ensure tnat instrument and facility projects explicitly consider the associated requirements for changes to infrastructure and operations at every stage of their development, where possible with the direct involvement of the ESO-Paranal operations team. The cost and effort associated with infrastructure or operations changes should be carefully estimated at each project stage and assessed at each stage review.

Integration of project teams

2. ESO should consider how projects can best integrate the consortium, ESO-Garching, and ESO-Paranal teams over the project lifetime to ensure transparent communications between these teams and a comprehensive flow of knowledge and expertise throughout the project. *Various ways of integrating the teams are worth exploring, and might be employed in different circumstances, including embedding members of one team in another, sending staff on regular visits between teams, frequent face-to-face interactions (in person or by video link), and regular email updates. ESO might*

ESO/VPHAS+ team. Acknowledgement: Cambridge Astronomical Survey Unit

Sometimes dramatic events are needed to create something stunning. This beautiful structure of filaments and clouds in the southern constellation Vela is all that remains of a massive star that died in a powerful explosion known as supernova. This is a small section of a larger image taken using the wide-field camera OmegaCAM at the VLT Survey Telescope (VST). Hosted at ESO's Paranal Observatory in the Chilean desert, the VST is one of the best telescopes in the world to take large images of the sky in visible light.

consider ways to bring younger staff (both scientists and engineers) into instrumentation projects this way.

3. ESO should examine whether there are long-term benefits to be had from earlier and stronger engagement by the ESO-Paranal operations team in PIP projects. If so, ESO should consider how to facilitate such engagement without placing additional burdens on the operations team, either in the long term or during any transition phase before benefits are realised. It may be appropriate to trial such an approach on one or more PIP projects.
4. ESO should also consider how to engage the ESO-Paranal operations team more effectively in reviews, both so that operational requirements and implications are fully examined and so that reviews provide assurance to the consortium and ESO-Garching follow-up team that commissioning and operations plans are viable.
5. ESO should consider how to encourage constructive engagement and ongoing support for instruments and facilities well after PAC by both consortia and ESO-Garching.

Reviews and documentation

6. ESO should carry out a 'review of reviews' for all its instrumentation programmes, as is currently planned. This should consider, amongst other issues, the mixed experiences of the projects covered by this Lessons Learned exercise and the various concerns they have raised.

Communication

7. ESO should provide and share best-practice guidelines for ensuring effective and transparent communication between consortia, ESO-Garching and ESO-Paranal. *Amongst other things, these guidelines might cover the proper use of formal and informal communication channels, codes of conduct for professional communications, and appropriate processes for resolving conflicts. They might usefully draw on the experiences from previous projects of both ESO staff and external consortia, and be part of the reference material for new project teams.*
8. ESO should ensure that key personnel in the consortia, ESO-Garching, and ESO-Paranal teams are made aware of significant context-setting information (such budgetary or resourcing forecasts, or the relative prioritisation of projects) to allow informed project planning.
9. *ESO may consider providing a short training course for key personnel (both internal and external) involved in proposing or initiating projects. The course might introduce the basic functioning of ESO and the PIP programme, and share a distillation of accumulated 'project lore' from earlier projects (both the internal view from ESO and the external view from previous Consortia). ESO might also consider integrating this course with a wider effort to update and improve the processes and documentation for all projects, capturing 'lessons learned' as a continuing exercise within ESO.*

Contractual relations

10. ESO should explore a variety of approaches to fostering better collaborative partnerships with consortia for instrument projects and avoiding adversarial contractual relationships. *The panel recognises that this is a fundamentally difficult problem that requires careful hands-on management in every single instance. However, keeping contracts as simple and clear as possible and constructively managing the relationship are essential ingredients, along with a greater degree of interaction and better communication, as per recommendations above. Reforming or streamlining the Change Control Board (CCB) process at Paranal to make it more collaborative and efficient also has the potential to improve relations*.
11. ESO should be an exemplary partner in projects where it is providing significant components of the instrument or facility, delivering products and documentation that are at least of the standard demanded of consortia. This requires ESO to appropriately resource ESO-Garching staff delivering the components, ESO follow-up teams, and ESO-Paranal operations teams.

VLTI strategy

12. ESO should more clearly define and socialise its development strategy for the VLTI, particularly regarding its own role and capacity to advance the VLTI relative to that of external consortia. *If ESO is to continue to play a leading role in developing the VLTI, then it will likely need to strengthen its in-house capabilities for both VLTI science and technology*.

Technology standards

13. ESO should continue to develop appropriate technology standards and require their use in instrument/facility projects, balancing the benefits of standardisation against the advantages of new technologies.
14. ESO should consider when in a project's lifecycle it is appropriate to impose standards, and how to fairly mitigate cost and schedule delays due to late imposition. *ESO may find it helpful to develop guidelines (or even policy) on this point*.
15. ESO should explore the opportunities for efficiency savings by making in-house expertise on ESO software standards more available to consortia.
16. ESO should continue to develop technical solutions in strategic areas that are required by, or could be transformative for, several instruments.

In-house capabilities

17. ESO should develop a strategy for its in-house technical capabilities that meets the needs of its longer-term instrumentation plans, retaining key expertise by continuing to develop instruments in-house. *ESO should consider in which areas it needs to retain deep expertise in-house and which it can delegate to the astronomy community or close industry partners.*
18. ESO should develop a succession plan, in line with this strategy, for the significant number of senior instrumentation managers and expert technical staff retiring in the next few years.

Short-term hirings

19. ESO should explore ways and means to provide additional flexibility in technical staffing to allow its instrumentation programme to respond more effectively to short-term demands.

Fragmentation and churn

20. ESO should consider measures to reduce the degree of fragmentation in technical staff effort and the churn of staff through projects. *ESO might explore the potential benefits and costs of imposing a minimum level of commitment of staff to projects, a maximum number of projects for each staff member, and a minimum duration for commitments to projects.*
21. ESO should encourage project managers to request the FTEs they really require, not just what is reasonable within extant constraints, to ensure ESO has a clear and accurate picture of its programme resourcing needs.

Software pipelines

22. ESO should explore the benefits and costs of enabling its user community to have access to software pipelines developed by consortia or specialised user communities, without ESO committing support or guaranteeing outcomes.

Remote access

23. ESO should develop and extend the remote access capabilities for its facilities and make such capabilities more widely available to observers and instrument developers. *ESO may need to assist with solutions to logistics issues experienced by users of its remote access facilities.*

Future projects

24. ESO should ensure all instrumentation and facility projects have clearly defined science drivers, and that these science drivers are re-assessed whenever a project descopes or changes are required for technical or financial reasons, or when external developments alter the scientific landscape.
25. ESO should explore ways to combine a disciplined approach to starting new projects with positive support for the development of new instrument/facility concepts in the community. *This may require a more competitive procedure for project selection at an early stage.*
26. *ESO might consider being more intentional about bundling small projects into larger projects and, conversely, splitting large projects into smaller projects (or stages)—particularly for internal infrastructure projects, but perhaps also for consortia-led projects.*

PIP resourcing

27. ESO should seek to increase efficiency in the staff effort it provides for VLT/I instruments and/or increase the amount of staff effort committed to the PIP in order to achieve its stated goal of maintaining a full, front-rank instrumentation suite on the VLT/I.
28. ESO should ensure strong and competitive instrumentation for the VLT/I despite pressure from the ELT and its instruments. ESO might consider merging the VLT/I and ELT instrument programmes to improve efficiency and coordination; however, any merged programme must guarantee a state-of-the art instrument suite for the VLT/I as well as for the ELT.

Acknowledgements

The 2023 Lessons Learned review panel wishes to thank all the ESO staff and members of the various instrument consortia who participated in this process, giving so generously of their time and sharing their hard-won experience in order to help ESO improve its already outstanding performance in providing world-class instruments and facilities to the ESO user community.

S. Bloemen (Radboud University)/ESO

The BlackGEM array, consisting of three new telescopes located at ESO's La Silla Observatory, has begun operations. This photograph shows the three open domes of the BlackGEM telescopes under a stunning night sky a La Silla. Other telescopes at the observatory are visible in the background.

DOI: 10.18727/0722-6691/5352

Infrastructure Upgrade of UT1, UT2 and UT3 for the Implementation of Laser Guide Stars for the GRAVITY+ Project

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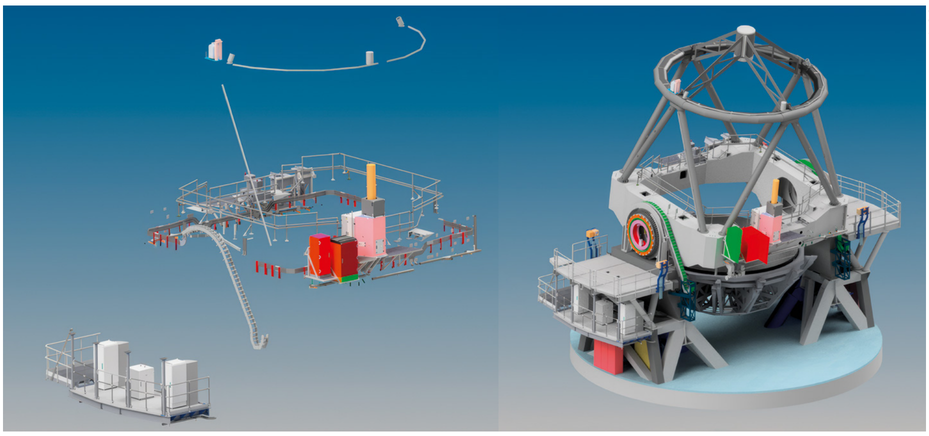
The GRAVITY+ project encompasses the upgrade of the Very Large Telescope Interferometer infrastructure and of the GRAVITY instrument to improve sky coverage, high-contrast capabilities, and faint science. The sky coverage is obtained by the use of one laser guide star on each Unit Telescope, but it first required an upgrade of the infrastructure of the telescopes, carried out over the last 18 months.

Introduction

The GRAVITY+ project (GRAVITY+ Collaboration, 2022) was launched in January 2022 after a year of conceptual study (phase A). It includes the development and implementation of one new laser guide star (LGS) single-conjugate adaptive optics (SCAO) system to replace the Multi Application Curvature Adaptive Optics modules (Arsenault et al., 2003) in operation since 2005 on each Unit Telescope (UT) of the Very Large Telescope Interferometer (VLTI). This module is implemented in the coudé path of the UTs with the deformable mirror at the position of the M8 mirror and the wavefront sensor in the coudé room which also contains the Star Separator and the Coudé Infrared Adaptive Optics Module. The LGSs are being developed in synergy with the Extremely Large Telescope programme. The design is based on those developed for the Adaptive Optics Facility (AOF; Arsenault et al., 2006, 2010, 2016) implemented on UT4. The laser itself is being developed by the German company TOPTICA and the Laser Projection Sub-unit (LPS) by the Dutch organisation TNO. The implementation of such a laser on the centrepiece of a UT necessitates a full upgrade of its infrastructure, which impacts the telescope from the top ring to the basement. Only UT4 is not affected by this upgrade requirement, given that it is already equipped with four lasers for the AOF. We require only one LGS per UT for GRAVITY+ so we decided to implement it on the side opposite (Nasmyth B) the optical coudé path used for the interferometer (Nasmyth A), so as to limit any potential vibration contamination coming from the cooling system and the electronics cabinets needed for the LGS.

Overview

A LGS is a complex system made up of several components implemented on several areas of the telescope (Figure 1).



Michael Tucker Booth/ESO

Figure 1. Left: components implemented on the UT. Right: 3D view of the components on the UT.

Figure 2. Some of the team at the end of the UT2 centrepiece intervention in April 2023.

From top to bottom, we start with the Aircraft Avoidance Camera which is implemented on the top ring of the telescope and developed by the Italian company Astrel Instruments. It detects the approach of an aircraft and automatically closes the laser shutter if the aircraft gets too close to the laser beam. The Laser Pointing Camera (also from Astrel), which precisely defines the position of the laser on the sky, is also implemented on the top ring. The Laser Projector Sub-unit, a large optical tube 40 cm in diameter that is used to project the laser on the sky, is implemented on the centrepiece. Beside the optical tube lie the laser cabinet itself and the electronics cabinets for the LPS.

On the side of the telescope under the Nasmyth B platform, a new heat exchanger produced by the Italian company Tecoelettra and laser electronics Nasmyth cabinet are located on a newly implemented platform. Finally, in the basement the pumps to provide the cooling for the electronics cabinets and the laser are housed.

None of the UTs was developed — 30 years ago — with the infrastructure needed to carry such a system. The upgrade included a full adaptation of the centrepiece, an upgrade of the altitude cable wrap on side B, the implementation of a platform under the Nasmyth B (to carry the heat exchanger and one electronics cabinet) and the implementation of a cooling circuit from the basement to the sub-Nasmyth platform via the azimuth cable wrap.

These activities required two missions per telescope, corresponding to 30 nights out of operation per telescope. The adaptation of the centrepiece also required the removal of the primary (M1) mirror cell. We therefore coordinated our activities to benefit from the regular (every 18 months to 2 years) recoating of the M1 mirrors so as to minimise the number of nights out of operation. We also took the opportunity afforded by the recoating of the M1 of UT4 in May 2022 to make a thorough inspection and ensure that we had all the information needed to start work on UT3 in August 2022.

This work package had a highly constrained schedule, defined on the one hand by the recoating schedule of the M1 of the UTs (on average two UTs are recoated per year) and on the other hand by the need to deliver the work package before the Assembly, Integration, and Verification (AIV) of the GRAVITY+ adaptive optics modules planned in 2024. We decided not to follow a classical project development approach (design, then procurement, then manufacturing, etc.) but instead to do all of these activities in parallel, based on the knowledge gained from the AOF project 10 years ago. It required us to work with a lot of unknowns that could only be addressed progressively and we were able to correct errors thanks to the fact that we required two missions per telescope; we planned each set of two missions with enough time between them to prepare the needed corrections.

Finally, we also used the synergy with the upgrade of the Visible and Infrared Survey Telescope for Astronomy (VISTA) needed for the 4-metre Multi-Object Spectrograph Telescope (4MOST; De Jong et al., 2019) to employ a dedicated team from Paranal contractor LINKES to work on both projects. Around 60 people (Figure 2) participated in at least one of the seven missions that covered this global upgrade. It corresponds to 7.5 staff years of work and 36 missions from Europe to Chile.

Safety

This upgrade necessitated working at height, crawling inside the centrepiece, manipulating heavy loads, drilling, grinding etc. Safety was therefore one of the most fundamental aspects of the project. A scaffold (Figure 3) was necessary to safely access all the parts of the telescope, and the staff working on the top of the centrepiece were equipped with harnesses fixed on safety lines. Each manipulation of a heavy load was made by certified persons. Some specific tasks, such as the reconnection of the motors of the M1 cover (which protects the primary mirror), also required the use of an aerial lift.

All the activities were coordinated with the Paranal Safety Office and every morning the work started with a reminder of the safety rules applicable to that day. We succeeded in avoiding any injuries, but we did have few near-miss incidents, all linked to dropping small objects such as screws. The largest object dropped was a one-litre plastic bottle, from the dome roof during cleaning.

We also implemented a safety barrier all around the centerpiece to allow better protection than afforded by the former safety line (Figure 4).

Scaffolding

We had two different versions of the scaffolding, depending on the type of activity. The larger one was dedicated to the upgrade of the centrepiece and the smaller one was for the work on the altitude cable wrap B. The implementation of the scaffolding was contracted to the Chilian company AKSIOM, which allowed it to be fully designed, tested, and certified. The larger one, which weighed 9 tonnes, required a day to implement by 10 persons.

Centrepiece

The centrepiece is the backbone of the telescope; it supports on its lower side the primary mirror cell and on its upper side the Serrurier truss which in turn supports the top ring, the spider, and the secondary mirror. The centrepiece rotates around the altitude axis, so the power, cooling, and data transmission needed to control the secondary mirror and the primary mirror cell are transferred via the altitude cable wraps and the centrepiece. Upgrading the centrepiece

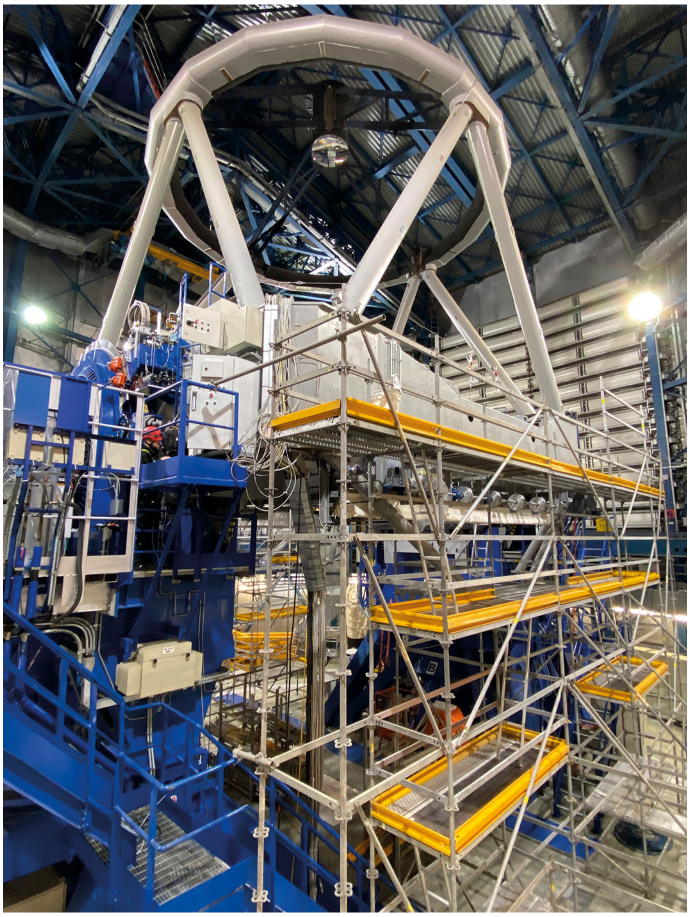


Figure 3. Scaffold erected on UT3 during the upgrade of the centrepiece in August 2022.

Juan Beltran/ESO

Figure 4. UT2 centrepiece at the end of the intervention in April 2023.

Figure 5. Inside the centrepiece of UT1 in August 2023.

required the transfer of all the cables, hoses, and pipes from on top to inside the centrepiece (Figure 5), the drilling and tapping for the later implementation of the LGS, the implementation of cable trays, cables and hoses dedicated to the LGS and the integration of a safety barrier to ensure that no one could fall when working on the LGS. This upgrade required around 1200 holes per UT to be drilled and more than 500 threaded, several areas to be cut and ground (Figure 6) to allow a better interface contact, 100 metres of cable trays to be added inside and on the side of the centrepiece, and 120 metres of hoses and a kilometre of cables to be fixed onto the cable trays.

Amusingly, inside each centrepiece, in the same area on the side of Nasmyth B, we found the remains of one cigarette butt left by workers during the manufacturing of the centrepiece 30 years ago, as if it was a kind of signature.

Altitude Cable Wrap

The altitude cable wrap routes all the cables and hoses needed for the centrepiece, the primary mirror cell, and the secondary mirror. Each UT has two altitude cable wraps, one on each Nasmyth side. The LGS, that projects a laser of 20 W, requires a lot of electrical power and consequently a lot of cooling power. A high-speed data transmission line is also needed to allow its control. All these hoses, cables and fibres must go via the altitude cable wrap. We only needed to upgrade the altitude cable wrap on side B. These cable wraps have been in operation for 25 years (first light of UT1 was in May 1998; see Giacconi, 1998). They carry the marks of age and of good service. We used the opportunity of the upgrade to replace all the roller bearings and plates, in hopeful expectation of 25 more years of good service.

The extraction of the altitude cable wrap, which weighs around 400 kilograms, is a complex intervention which requires 10 people and the use of the dome crane and several chain hoists (Figure 7). It is lowered centimetre by centimetre onto the azimuth platform. The replacement was even more complex than the extraction as we had to take care to not damage any cables or fibres inside the cable wrap.

The cable wrap, when installed, is connected on its two sides to so-called junction boxes. They contain hundreds of electrical and optical connections. These two cabinets also had to be removed and replaced with bigger ones to allow the needed connections for the LGS and the implementation of the controllers for the Aircraft Avoidance Camera and the Laser Pointing Camera, which are both installed on the top ring of the UT. This reconnection takes on average four days by five to six persons.

Sub-Nasmyth B Platform

The sub-Nasmyth B platform is located 3 metres directly under the Nasmyth platform. It is made of two structural sections, the largest one being 8.5 metres wide and weighing a bit more than one tonne. They were manufactured in Europe and transported by ship. They were the largest elements of this upgrade. It took six people over four days to implement the two platform structures (Figure 8). The structure of the telescope had to be ground, drilled, and tapped to allow a good surface contact at the bolted connection between the platform and the structure. This platform is linked to the Nasmyth platform by four pillars. It will carry three cabinets for a total load of around one tonne.

The implementation of each platform section was basically made in two steps: first the dome crane was used to bring the platform close to its final position then several chain hoists were used to allow the precise positioning before being bolted. The grating and the handrails could then be fixed on to the platform.

Figure 6. Grinding the surface of the telescope structure to ensure a smooth interface.

Figure 7. Implementing the upgraded cable wrap at Nasmyth B on UT2 in June 2023.

Figure 8. Transfer of the largest part of the sub-Nasmyth platform B on UT2 in June 2023.

Cooling from basement to centrepiece

The pumps for the cooling are in the basement of the telescope. It means that the two cooling circuits needed for the LGS must be routed via the azimuth wrap, the altitude wrap, and through the centrepiece, to finally reach the electronics cabinets attached to it. One circuit requires very precise temperature control for the laser itself and then it is connected to the heat exchanger on the sub-Nasmyth platform. The second circuit follows the standard implementation on Paranal, and its temperature is controlled compared to the dew point. Finalising the implementation of the cooling is the last step of the upgrade and it is planned to be completed in the first semester of 2024.

Conclusion

The upgrade of the UTs was the first step in implementing the LGSs on the UTs. The LGSs themselves will be implemented in late 2025. They are being installed to increase the capabilities of the VLTI; the use of the LGSs for GRAVITY and the VLTI will increase the sky coverage by an order of magnitude compared to the current capability.

But it will also be possible to use them for future instruments or if existing instruments are upgraded with the LGS SCAO system. This UT upgrade has also been done in such a way that it is already possible to implement several additional LGSs per telescope without a major intervention necessitating the dismounting of the M1 or of the cable wrap.

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DOI: 10.18727/0722-6691/5353

Goodbye SOFI and Thanks for 25 Years of Data!

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15 August 2023 was the last night of observation with Son OF Isaac (SOFI) at the New Technology Telescope (NTT) in La Silla. The following day, the instrument was warmed up and removed from the NTT's Nasmyth A focus, in preparation for Son Of X-Shooter (SOXS) to be installed in its place.

A little bit of (glorious) history

Son OF Isaac (SOFI; Moorwood, Cuby & Lidman, 1998) was a near-infrared (0.9–2.5 μm) spectro-imager and polarimeter installed at the Nasmyth A focus of the New Technology Telescope (NTT) in 1997; it saw first light on 6 December 1997[1] and entered into operation during 1998. The development of SOFI was exceptionally fast for a new instrument, taking less than two years, since many technical solutions already tested for the Infrared Spectrometer And Array Camera (ISAAC)[2] were adopted, i.e. identical detector acquisition system and control software.

SOFI was conceived as a near-infrared equivalent of the ESO Faint Object Spectrograph and Camera 2 (EFOSC2), a workhorse instrument, and it was dedicated to the exploration of the near-infrared Universe. SOFI was capable of taking images in several narrow- and broad-band filters at different spatial resolutions, and spectra with three slits (0.6, 1 and 2 arcseconds wide), delivering spectral resolutions ranging from R = 1000 to R = 2200 (with the 0.6-arcsecond slit).

A polarimetric capability was also commissioned and offered to users, making SOFI a versatile instrument with better performance than the InfraRed Array Camera 2 (IRAC2) at the MPG/ESO 2.2-metre telescope and the previous InfraRed SPECtrometer (IRSPEC) on the NTT, which SOFI replaced.

The new instrument paved the way for testing and using the Very Large Telescope (VLT) software on the NTT and allowed the regular use of Observing Blocks (OBs); the new Phase 2 tool could then be verified, standardising day and night operations, and leading to greater observing efficiency.

The other novelty with SOFI was to offer the community a new software capable of processing the various observing modes, such as jittered[3] observations, which greatly helped in dealing with the large amounts of data near-infrared instruments can generate. More importantly, it paved the way for the publicly available instrument pipelines that we see today.

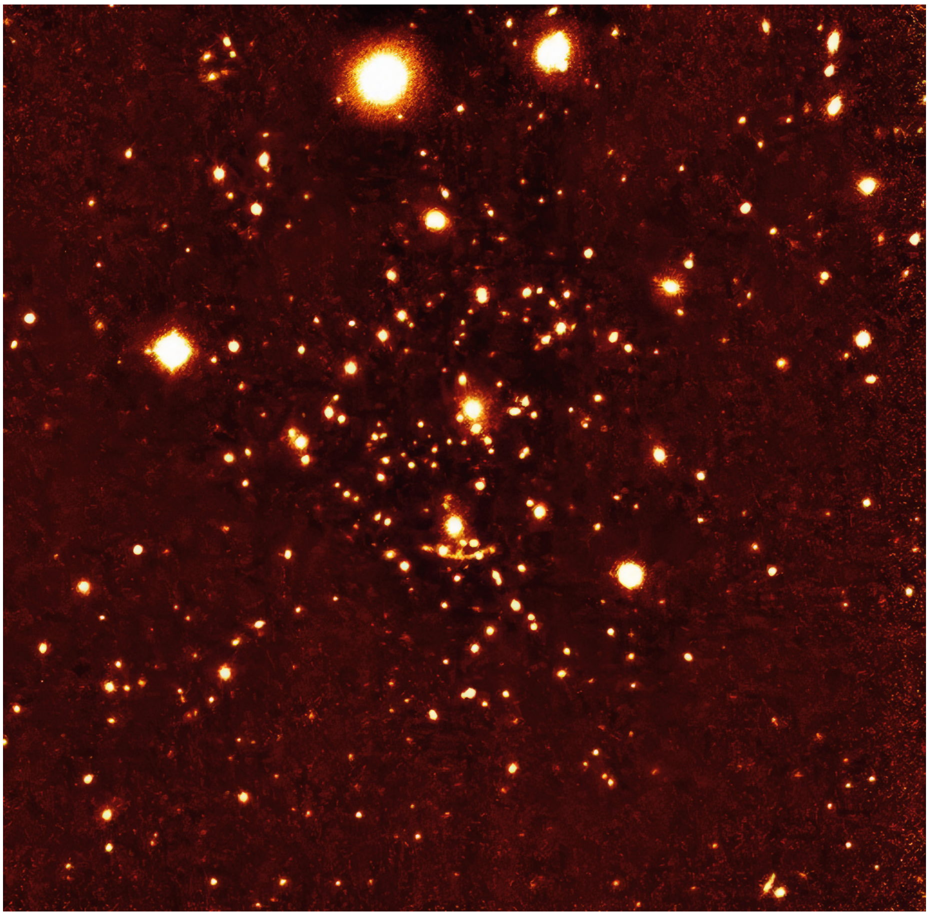

Figure 1. This is a J-band (1.25 micron) image of the galaxy cluster Abell 370 (z = 0.375), obtained in 'jitter' mode, showing the famous gravitational arc just below the centre. The observations consisted of 24 exposures of two minutes each, made on randomly generated telescope positions within a sky region of 30 × 30 arcseconds. The individual exposures have been sky-subtracted using a running average determined from the same data and then re-centred and combined. The scale is 0.29 arcsec pixel^{-1}; the field is about 5 × 5 arcminutes with north at the top and east to the left.

Technical challenges

A cryogenic instrument needs to be warmed up for any technical intervention on the cold components and SOFI was no exception. The warming/cooling cycle needs time to avoid thermal shocks on the components and the same components need to be built using special materials which will work correctly both at room temperature for testing, and at cryogenic temperatures. SOFI had several of these interventions, both to improve its performance and to fix broken parts; special care was taken during the thermal cycles to ensure the integrity of the instrument and a dedicated clean space was set up in the Nasmyth A room to work on the maintenance of the components.

The other interesting challenge was data reduction, in particular to flat-field the data; the shading effect on the detector was found to depend on the flux, which led to the development of special templates for the dome flat-fields, where a set of images were taken with the detector only partially illuminated to allow for an estimate of the shading when the lamp was on with respect to the dark frames. On the data reduction side, Nicolas Devillard played a fundamental role in writing the data reduction algorithm[3] but help was needed from astronomer colleagues to explain the ins and outs of astronomical data reduction and the structure of a FITS header.

Scientific achievements

Being a workhorse instrument, SOFI had a large and varied community of users. Among many scientific highlights were: the combined observations with other instruments of SN1998bw, the first hypernova ever associated with a long-duration gamma-ray burst (Iwamoto et al., 1998); the first large extragalactic surveys in the near-infrared (the K20 survey; Cimatti et al., 2002); and imaging of the famous 'deep fields' in the southern hemisphere, the Chandra deep field (Hatziminaoglou et al., 2002; Moy et al., 2003) and the Hubble deep field (Vanzella et al., 2002). Closer to home, SOFI played an important role in the Araucaria project[4], aimed at improving the calibration of the cosmic distance scale in the local Universe, which led to many seminal papers, and in observations of newborn stars. Even closer to home, SOFI was used to observe sources in the Solar System and even supported space missions (mostly lunar observations).

Beside the vast scientific production, SOFI yielded beautiful images too, which were also featured in NASA's Astronomy Picture of the Day[5].

Concluding remarks

As with any other workhorse instrument, SOFI has served a large fraction of the astronomical community with a variety of scientific programmes, something fundamental for the large number of users ESO has. The intense demand for workhorse instruments continues to the present day, as is evidenced by the large pressure factors on the Ultraviolet and Visual Spectrograph (UVES), the FOcal Reducer and low dispersion Spectrographs 1 and 2 (FORS1, FORS2), X-shooter and the Multi Unit Spectroscopic Explorer (MUSE), some of which are only a few years younger than SOFI.

Many astronomers — Jean-Gabriel Cuby, Malvina Billeres, and the authors of this paper — have served as instrument scientists for SOFI. Some were already familiar with near-infrared instruments, but for others, SOFI was their first taste of observations in the near-infrared. SOFI, on top of its many achievements, was a patient teacher.

Acknowledgements

We wish to thank all the telescope operators who have helped with running SOFI, and all the colleagues from Chile and Garching who have contributed with their work to the smooth operation of the instrument.

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ESO/A. Ghizzi Panizza (www.albertoghizzipanizza.com)

Standing majestically at the top of a hill at ESO's La Silla Observatory, surveying the watercolour scenery of another sunset in Chile's Atacama Desert, is the New Technology Telescope (NTT). It has been ticking along, making discovery after discovery, ever since it was inaugurated in 1989. Its home at La Silla sits at an altitude of 2400 metres and is far from sources of light pollution, giving the NTT uninterrupted views of the Universe.

DOI: 10.18727/0722-6691/5354

HARPS at 20: Evolving Through Continuous Improvements

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The High Accuracy Radial velocity Planet Searcher (HARPS), operational since October 2003, has been pioneering exoplanetary research, with over 1300 publications and more than 200 exoplanet detections, and is still in high demand. Its continued success has been achieved thanks to its extraordinary stability, the continuous improvement of its data reduction pipeline and the integration of innovative technologies whenever they became available. Here we report on the recent maintenance mission to enhance the detector's cryostat reliability and thermal stability. Additionally we tested a novel cryogenic concept on HARPS, and the positive outcome of the test opens up new possibilities.

The High Accuracy Radial velocity Planet Searcher (HARPS) started science operations at ESO's 3.6-metre telescope in La Silla on 1 October 2003 (Mayor et al., 2003; Pepe et al., 2003). The twenty years that have passed since then have seen more than 1300 HARPS publications. The 1 m s^{-1} radial velocity (RV) precision barrier has been largely surpassed, and we have learned much about extra-solar planets thanks to the more than 200 detections made with this instrument (see, for example, the NASA Exoplanet Archive[1]). We have understood how common and how diverse extra-solar planetary systems are, and we are now characterising some of these planets, determining their density with the help of transit measurements (Armstrong et al., 2023), and even their atmospheres (Prinoth et al., 2022). Today, HARPS remains one of the most requested instruments at ESO.

One of the main performance indicators for Extremely Precise Radial-Velocity (EPRV) spectrographs like HARPS is measurement repeatability over a long period of time. To achieve this the instrument is optimised for mechanical stability, operated in a vacuum, thermally stabilised and closely monitored. These features put HARPS at the top of its class of instruments. Furthermore, and for all these years, HARPS's performance has been continuously improved whenever the conditions and the technology made it possible. In 2010, for instance, a new guiding system was integrated at the 3.6-metre telescope, enabling faster and more accurate corrections (Ihle et al., 2010). HARPS was the first high-resolution spectrograph to routinely use a Fabry-Pérot source for drift monitoring (Wildi et al., 2011) and a laser frequency comb (LFC) for wavelength calibration (Wilken et al., 2012; Lo Curto et al., 2012), a strategy today employed by most EPRV spectrographs.

In 2015 the HARPS vacuum vessel was opened for the first time after 11 years of continuous operation to replace (following the successful example of its northern twin HARPS-N), the old fibre link with new octagonal fibres for better light scrambling and thus improved RV precision (Lo Curto et al., 2015). This intervention, accompanied by an optimisation of the image quality (refocusing), caused, however, a RV discontinuity of the order of 10 m s^{-1}, depending slightly on stellar temperature and rotational velocity; users must take this into account when combining RV datasets from before and after this intervention, which was in May 2015.

The hardware is not the only component that underwent various improvements over the years; the software, in particular the reduction pipeline, was in continuous evolution, as the instrument enabled us to explore uncharted territories.

A new upgrade, aimed at refurbishing the vacuum gauges and a faulty temperature sensor in the cold plate of the liquid-nitrogen-cooled detector cryostat was executed between 14 and 28 November 2023. Although this intervention had been planned and prepared for more than a year, just three weeks before the start of the mission a leak developed in the cryostat which caused operational troubles; the intervention did not come a minute too early.

During the technical mission, the vacuum line was upgraded with new gauges and three-way valves for ease of future gauge maintenance; additionally, a comprehensive rewiring of the detector unit Continuous Flow Cryostat (CFC) was undertaken to prevent electrical short-circuits. More importantly, the faulty sensor regulating the cold plate temperature

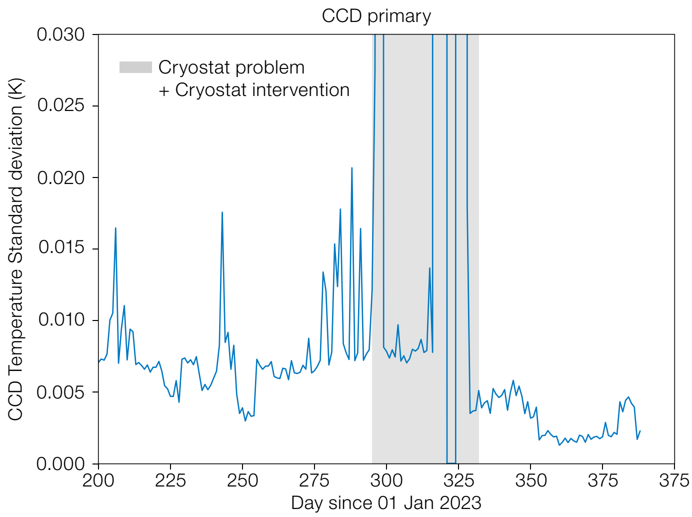

Figure 1. One-night peak-to-valley (PtV) temperature variation of the HARPS CCD with time. The increase in thermal stability after the intervention is clearly visible on the plot (rightwards from the grey band).

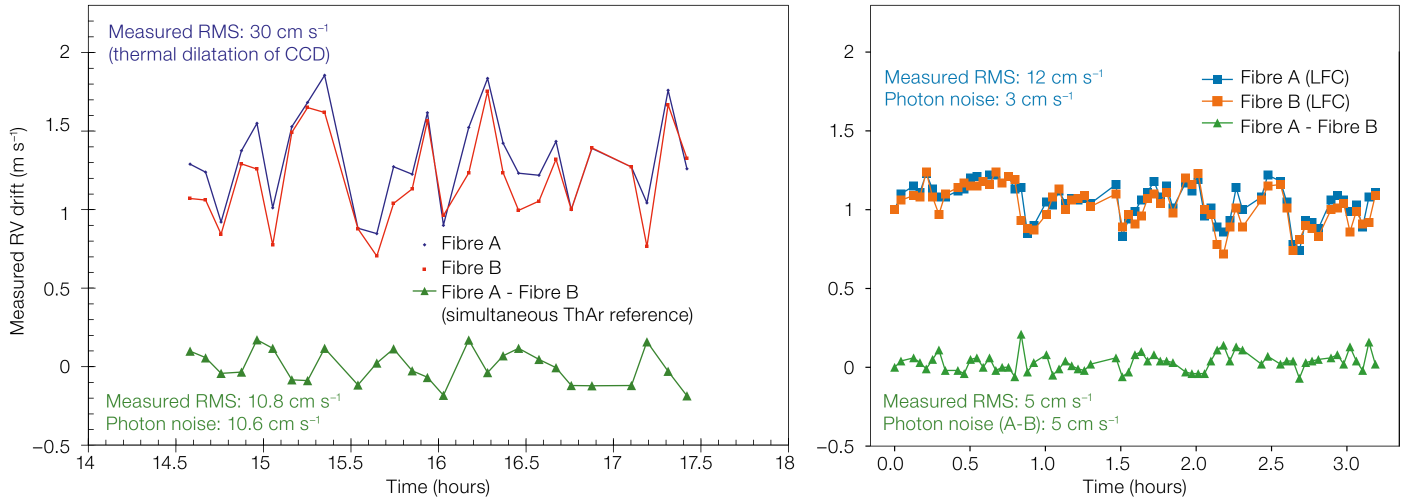

Figure 2. Instrument stability measured with the ThAr hollow-cathode lamp in 2003 (left), and with the LFC in 2023 (right). Plots are on the same scale; the improved instrumental stability is clearly visible. The plot on the left is from Mayor et al. (2003).

and the cold plate itself were exchanged. The purpose of this operation was to improve operational reliability and possibly increase the thermal stability of the detector. As illustrated in Figure 1, this latter goal was fully achieved and the results are impressive: while before the upgrade the CCD temperature could vary by up to a few times 0.1 K, after the upgrade the system is capable of maintaining temperature stability at the level of the resolution of the Lakeshore temperature controller, i.e., to better than 0.01 K. The improved thermal stability of the detector is reflected directly in improved repeatability of the RV measurements. Indeed, the standard deviation of the drift measurement on each of the two HARPS fibres over a short-duration sequence of LFC spectra has decreased by almost a factor of two, (from approximately 22 cm s^{-1} to about 12 cm s^{-1}; Figure 2) after the mission, very close to the photon noise. This induces, in turn, an overall decrease in instrumental noise in the wavelength calibration and in the consequent RV measurements.

The intervention on the cryostat required opening the vacuum vessel, a very delicate operation with a possible impact on the spectral format of the instrument; utmost care was needed to prevent any modification of the spectral format and the line profiles. The (physical) movement of the spectrum on the detector has been quantified at 0.7 pixels along the main dispersion direction and 1 pixel in the cross-dispersion direction. More importantly, no RV offset was measured within the measurement scatter (photon noise around 30 cm s^{-1}) on a set of three standard stars of different spectral types acquired before and after the mission (Figure 3).

The access to the current CFC during this latest maintenance mission, and the timing alongside other ongoing upgrade projects at ESO, made it possible to also test on HARPS a novel cryogenic cooling concept, with the goal of replacing both the ESO standard liquid nitrogen CFC and the bath cryostat with a very compact commercial off-the-shelf Stirling cryocooler[2]. The extreme metrological precision of HARPS was the main motivation for performing the test, because even tiny displacements of the spectral lines — due to vibrations — of a calibration source could have been detected. The result is extremely promising, showing no effect on the positions of the spectral lines induced by the residual vibrations of the CryoTel GT Stirling cooler. The uncertainty of the measurement was of the order of 30 cm s^{-1} in RV, corresponding to a global displacement of the spectral lines on the detector of about 5 nm, only about 10 times larger than the silicon lattice constant.

The success of this test opens the window to considering the possibility of an upgrade of the HARPS detector system with a new cryostat cooled with a CryoTel GT AVC generation II, and possibly an improved, 4k × 4k monolithic detector, in place of the current mosaic of two 2k × 4k chips. While this upgrade might improve the instrument performance even further (in terms of stability and spectral coverage), it would certainly address the issue of the technological obsolescence of the control electronics, now 25 years old, and also possible failures of the current and quite aged CFC on an instrument that is still one of the best of its kind worldwide. Furthermore, it could be used as the perfect test bench in view of the deployment of new controllers and cryocoolers on various other instruments, such as the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) on the Very Large Telescope and the future ArmazoNes high Dispersion Echelle Spectrograph (ANDES) on ESO's Extremely Large Telescope.

The future of HARPS therefore remains bright as regards its own capabilities and scientific mission, its combination with the Near InfraRed Planet Searcher (NIRPS), its infrared twin on the 3.6-metre telescope, and the connection of both instruments to the HARPS Experiment for Light Integrated Over the Sun (HELIOS)

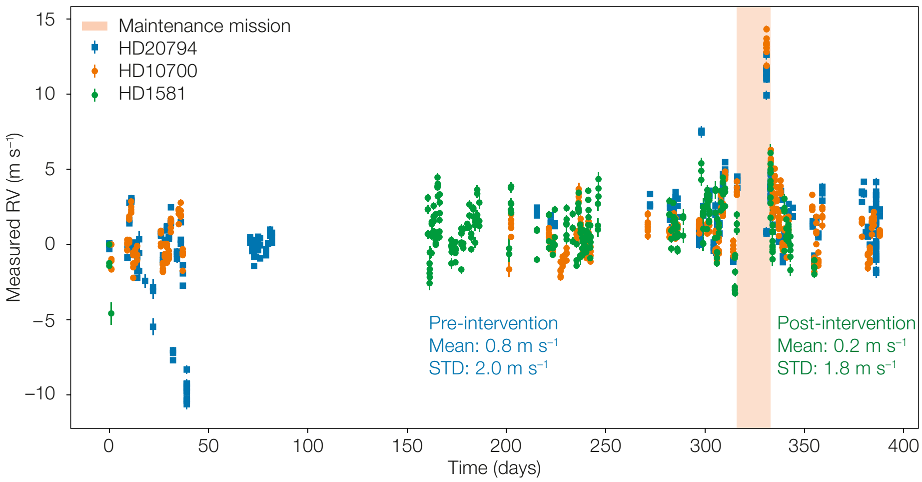

Figure 3. Radial velocity variation of a sample of quiet stars used for instrument stability monitoring. Within the scatter of the measurements no discontinuity is visible in the radial velocities after the completion of the mission.

solar telescope. HARPS and La Silla are furthermore the ideal platform on which to implement and test cutting edge technology.

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ESO/PHANGS

This is an image of the spiral galaxy NGC 4303, also known as Messier 61, which is one of the largest galactic members of the Virgo Cluster. Being a so-called starburst galaxy, it has an unusually high number of stars being born, and has been used by astronomers as a laboratory to better understand the fascinating phenomena of star formation.

The golden glow is a result of combining observations taken at different wavelengths of light with the Multi-Unit Spectroscopic Explorer (MUSE) instrument on ESO's Very Large Telescope (VLT) in Chile. Here gas clouds of ionised oxygen, hydrogen and sulphur are shown in blue, green and red, respectively. The observations were made as part of the Physics at High Angular resolution in Nearby GalaxieS (PHANGS) project, aiming to study nearby galaxies across all wavelengths of the electromagnetic spectrum.

ESO's observatories are based in northern Chile in the vast, arid expanse of the Atacama Desert. If one were to drive northward towards San Pedro de Atacama, one would see this view — a mountainous landscape stretching out as far as the eye can see, with strikingly clear skies overhead. This image was taken some 50 kilometres from the Chajnantor plateau, home of the ALMA observatory. The mound directly ahead is the Miñiques volcano complex, which is topped by clouds, seemingly pointing to the cosmos.

P. Horálek/ESO

P. Horálek/ESO

This little planet panorama concentrates in one image the scientific, technical and administrative centre of ESO, in Garching, near Munich. ESO's Headquarters are framed by a crane that is working on the construction of the ESO Supernova Planetarium & Visitor Centre.

DOI: 10.18727/0722-6691/5355

Report on the ESO workshop

Peer Review Under Review

held at ESO Headquarters, Garching, Germany and online, 6–10 February 2023

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The workshop Peer Review Under Review, held at ESO Headquarters in Garching, Germany from 6 to 10 February 2023, marked a significant milestone, being the first conference focusing on peer review within the astronomical community. This unique gathering not only convened representatives from many of the major astronomical organisations but also drew experts from such diverse fields as computer science, social sciences, statistics, meta-research, and other relevant domains. This unique group of experts critically examined the current state of peer review in the scientific community. This report summarises the presentations and discussions, and the conclusions that emerged during the workshop.

Figure 1. The workshop logo.

Introduction to peer review

Peer review (PR) is a cornerstone of academic knowledge production and dissemination, maintaining scientific rigour and quality by scrutinising research before publication. Despite its critical role, the PR process in its current form has been under scrutiny. The system, primarily established in the 18th and 19th centuries, is perceived by many to have lagged behind the rapid expansion and specialisation of the scientific community. With a 15% increase in the number of researchers between 2014 and 2018 and a two-fold increase in publications in the field of astronomy every 14 years, the strain on PR is evident.

There is an increasing call to adapt and innovate the PR process in sync with technological advancements and the surge in publication dissemination, as the current system is susceptible to stagnation and bias. Against this backdrop, ESO hosted a workshop entitled Peer Review Under Review, aiming to create a forum in which to review the current implementations of PR and to discuss its future in a digital and interconnected science community. The workshop was attended by representatives of a wide range of organisations, including ESO, ESA, the Joint ALMA Observatory, STScI, NASA, SKAO, and NOIRLab, and a significant group of non-astronomer experts in PR. The discussions were divided into four main sessions, focusing on: Peer Review at Large; Methodologies; Diversity, Equity and Inclusion; and Concrete Examples. Ample time was included for exchanges of ideas. This unique blend of participants allowed us to examine PR from various perspectives, learning from the experiences and methods of other fields, and hearing from researchers who study the PR process itself.

In the following sections we provide a short summary and highlights of the individual workshop sessions.

Peer Review at Large

The workshop session Peer Review at Large hosted an array of speakers who discussed the evolving landscape of PR in scientific research. The presentations highlighted the importance of adapting traditional systems to meet the challenges and demands of modern-day research. Several core themes emerged throughout the session, including the importance of diversity, transparency, fairness, efficiency, and evolution in the PR process.

The efficiency and evolution of the PR process were prominent aspects of this section. Tracey Weissgerber introduced an innovative project, ScreenIT, which employs automated screening tools for the initial evaluation of scientific papers, promoting efficiency and accuracy. Meanwhile, Mario Malički discussed developments in PR, including plagiarism checking, language software and semi-automated/AI checks, which all indicate a significant trend towards digitisation and automation.

Ludo Waltman addressed the mounting strain on the traditional PR system, suggesting alternatives such as preprinting and open PR, aimed at fostering genuine scientific conversations. Johanna Schnier, Christina Raasch, and Ferdinando Patat proposed re-evaluating resource allocation strategies, suggesting a two-step review procedure and dedicated funding schemes for resource-intensive proposals to avoid biases against such programmes.

This emphasis on diversity and inclusivity was echoed by Vicente Amado Olivo and Wolfgang Kerzendorf, who proposed a global registry for peer reviewers in astrophysics. Their goal is to broaden the scope of reviewers and counteract issues of author name ambiguity through innovative use of algorithms and ORCiD identifiers. This initiative resonates with Cornelia Schendzielorz’s and Martin Reinhart’s idea of democratising the PR process by enlarging and diversifying reviewer pools and ensuring more qualitative deliberation in the assessments.

Bias in PR was another central theme. Valentina Tartari, Hans Christian Kongsted, and Maryann Feldman highlighted biases in the allocation of scientific research funding. They suggested a more nuanced approach that takes into account factors such as career implications, visibility, and scientists’ past performance. Ferdinando Patat also tackled bias, presenting a statistical analysis of the proposal ranking process at ESO. He revealed the systematic effects that could be introduced in panel meetings. These help to minimise differences in reviewers’ opinions, leading to greater agreement among them, although this doesn’t necessarily mean the final evaluations are more accurate. Furthermore, ESO data indicate that agreement between reviewers is limited, suggesting the need for a broader statistical foundation to achieve more dependable evaluations.

Thierry Forveille provided a behind-the-scenes look at the PR process at *Astronomy & Astrophysics*, underlining the importance of selecting appropriate referees and ensuring swift responses. Similarly, Stefan Immler presented an inside perspective on NASA’s commitment to diversity, inclusion and equity in their PR processes, detailing the upcoming plans which include the introduction of Inclusion Plans for proposals and bias training for all peer reviewers.

Finally, Elena Erosheva focused on challenges associated with using numeric scores in PR settings. She proposed a combined approach of scores and rankings to enhance the accuracy and fairness of evaluations, providing a more comprehensive representation of quality estimation.

In conclusion, the presentations highlighted the need to re-evaluate and adapt PR practices to ensure they remain fit for the purpose in the modern research landscape. They pointed towards a future in which PR is more inclusive, diversified, fair, efficient and transparent, leveraging advancements in technology to improve its efficiency and effectiveness.

Methodologies

In a riveting discussion on managing the surge in submissions, Nihar Shah showcased an automated reviewer assignment system. The system crafts a reviewer pool, gauges similarity scores for each proposal-reviewer pair, and then allocates papers based on these metrics. Nihar took the participants through the computation intricacies, from topic intersections to text matching and even bidding, culminating with the introduction of the PeerReview4All algorithm which boasts effectiveness across varied evaluations.

Drawing attention to the potential pitfalls of the PR process, Rachel Heyard expressed concerns about the reliability of funding allocation through this method. She underscored the biases and inherent uncertainties that often mar the process, suggesting that attempts to train reviewers might fall short. Based on data from the Swiss National Science Foundation, Rachel made a compelling case for the adoption of lottery systems and continuous funding mechanisms, offering a fresh perspective that acknowledges the system’s inherent unpredictability.

On the topic of AI’s role in assessing journal articles, Mike Thelwall presented a deep dive, specifically examining the UK Research Excellence Framework (REF) 2021 and a selection of physics articles. Though AI displayed an accuracy range of 65–75% in its predictions based on a myriad of metrics, it occasionally fell short when matched against human judgment. However, the silver lining was AI’s knack for yielding unbiased results in certain spheres. While the experiment provided valuable insights, it’s important to note that it didn’t compare the deviation between AI and human evaluations with that between different human panels. Hence, one cannot conclusively determine whether the AI’s assessment deviated more significantly than what might be observed between two human panels reviewing the same proposals. This aspect remains a crucial consideration for interpreting the results, as pointed out earlier by Ferdinando Patat.

Returning to the spotlight, Nihar Shah shared insights on the burgeoning field of Distributed Peer Review (DPR) in computer science, notably its profound impact in the machine learning sector. He delineated the clear merits of DPR but didn’t shy away from mentioning challenges like ‘commensuration bias’ and ‘miscalibration’. Nihar’s analysis, highlighting potential fraud risks in DPR, also applies to classical panels, emphasising the universal importance of implementing preventive measures to ensure the integrity, soundness and quality assurance of each review process.

Continuing this enlightening session, Fabio Sogni and Dario Dorigo described the strides they had made towards enhancing the proposal submission and review system at ESO. By the close of 2021, ESO had seamlessly integrated the ground-breaking p1Flow project, ushering in transformative components like proposalDistributor and proposalManager. Their innovative algorithm, tailored for superior proposal-reviewer congruence based on scientific relevance, marked a significant milestone in PR at ESO. Looking ahead, the successful deployment of this algorithm in DPR sets a promising precedent for its future implementation in Panel Reviews, aiming to enhance the alignment and effectiveness across all review processes.

Lastly, to further underscore the ongoing advances in streamlining the PR process, David Harvey presented a talk on Prophy. Prophy is a tool that aims to modernise the scientific PR process. Moving beyond the traditional reliance on keywords for reviewer assignments, it utilises an AI-driven database of scientific articles. This approach facilitates the identification of appropriate reviewers by creating detailed profiles based on scientific concepts. While Prophy seeks to improve the fairness and efficiency of PR, it reflects an ongoing evolution in the field, with its effectiveness yet to be fully assessed in the broader scientific community.

The Methodologies session was a deep dive into the current challenges and innovative solutions shaping the landscape of PR processes. With a tapestry of expertise, attendees witnessed a rich exploration spanning automated systems, funding biases, AI's burgeoning role in evaluations, and the layered world of DPR. Such revelations underscored the pressing need to refine and reshape review methodologies to better cater to the scientific community's evolving demands.

Diversity, Equity and Inclusion

The workshop session on Diversity, Equity and Inclusion provided critical insights into the PR process and the imperative need for more inclusive research evaluations. Cassidy Sugimoto highlighted the importance of such inclusive evaluations, drawing attention to the urgent need to address biases and systemic challenges present in the current PR process. She pointed out that bias in respect of who gets to become a scientist and their scientific publications and activities starts early and accumulates at each career step, hence disfavouring scientific excellence. In particular, when gender is known, women are penalised. Therefore, anonymisation is essential to both minimise discrimination and promote excellence.

Andrea Rapisarda emphasised the often underestimated role of serendipity in scientific discoveries. Using historical examples like the discovery of penicillin and the finding of the cosmic microwave background radiation, Andrea showcased how many scientific advances owe their genesis to chance events. Despite this, the present science funding landscape may sideline the role of randomness, leaning instead towards a naïve meritocracy. This structure, according to Andrea's agent-based model, tends to favour the moderately talented yet lucky individuals. To nurture genuine talent and foster true innovation, Andrea championed funding strategies that provide expansive opportunities, moving away from just rewarding past successes.
The theme of randomness in the realm of scientific evaluation and funding was continued by Christophe Heger. Citing the study by Cole, Cole & Simon (1981), Heger highlighted that a significant fraction of funding decisions are influenced by the random choice of reviewers. This brings into question the current PR system's efficacy. Tracing the origins of PR, Christophe elaborated on its aims and inherent criticisms, primarily its potential biases. To address this, reforms such as introducing lotteries or blinded reviews were debated. While these methods promised a reduction in costs and biases, a survey revealed a notable resistance from the scientific community, with a significant majority opposing the integration of lotteries into grant decisions.

The finale of the randomness discussion was the Volkswagen Foundation's Experiment! Initiative presented by Ulrike Bischler. Between 2017 and 2021, this initiative experimented with a partial randomisation method for grant selection. In this implementation, randomisation was applied to applications which were peer-reviewed in the classical way and ranked in the central, grey area, where the evaluation confusion generated by the subjectivity of the process is inherently large.

Inspired by historical precedents, such as Athenian democracy's allocation methods, the initiative aimed to challenge the prevailing PR system's limitations, including biases and conservatism. As a result of this experimental approach, there was a marked increase in representation on the part of women, early career researchers, and underrepresented disciplines. Surveys further echoed the sentiment that the grantees found the lottery system more equitable and diverse. The comparison between traditional review and this randomised method revealed no discernible difference in project outputs, reinforcing the potential benefits of such an innovative approach.

As the discussions progressed, Virginia Valian dwelt on Evaluating Merit. One of the key points she brought forward relates to the fact that a significant portion of the scientists are still convinced that they are objective in their evaluations, while they are in fact just unaware of biases. Going one step further, for example, believing that there is no gender bias actually leads to a more pronounced discrimination. Dual anonymisation definitely helps, although it does not eliminate the differences related to gender-dependent writing styles. AI-based tools can help reduce these effects, also improving the situation for non-native speakers coming from disadvantaged backgrounds.

This was followed by Lou Strolger's discourse on "Reducing systemic biases through anonymized time-allocation peer review", and by Verne Smith's report on Planning and Deploying the NSF's NOIRLab Dual Anonymous Review Process. The experience of dual-anonymous PR in proposal evaluation shows that proposals from women and early-career scientists are evaluated more positively when their identity is not known.

In conclusion, this workshop session underscored the paramount importance of diversity, equity, and inclusion in the scientific PR process. The discussions provided a holistic view of the challenges present and the possible avenues for future reform. As the scientific community grapples with these issues, the overarching sentiment remains: a call for a more inclusive, unbiased, and innovative system that truly fosters talent and ground-breaking research.

Concrete Examples

The workshop session on Concrete Examples offered participants an in-depth exploration of diverse observatory systems and the challenges and transitions they have faced in their PR processes.

ALMA, represented by Andrea Corvillón and John Carpenter, transitioned from a panel-based system to a DPR system in Cycle 8, as a result of an escalating number of submissions. This marked a significant development in astronomy PR, with the engagement of over 1000 individual reviewers evaluating around 1500 proposals. Feedback suggested concerns over proposal assignment and reviewer expertise, but it was noteworthy that junior researchers, including students and postdocs, provided reviews that were as constructive as those of senior counterparts. ALMA envisions enhancing this system with advanced algorithms and machine learning for better proposal assignments.

André-Nicolas Chené from NOIRLab, the US focal point for nighttime astronomy, showcased its PR system that handles over 1000 proposals annually for its semi-independent observatories. Notable in the presentation was the introduction of the Dual Anonymous Review Process and the Research Inclusion Initiative. The latter emphasises a democratic approach to scientific contributions, aiming to broaden accessibility to research opportunities.

The Australia Telescope National Facility (ATNF), a branch of Australia’s CSIRO represented by Elizabeth Mahony and Philip Edwards, has seen its Time Assignment Committee (TAC) process evolve over three decades. Today, the ATNF TAC, which includes both national and international members, reviews submissions from nearly 700 astronomers globally. A commitment to countering unconscious bias led to a transition from semi-anonymisation to complete anonymisation in 2022.

Norbert Schartel discussed the XMM-Newton mission and presented its unique PR system, stressing minimal interactions between mission staff and reviewers. With panels of experts from various countries, the system encourages diversity and inclusion while aiming for robust scientific advancements. This method serves as a bridge between the mission and the scientific community, integrating them more closely.

Rodolfo Montez illuminated the workings of the Chandra PR process. Chandra, a space-based X-ray observatory under NASA, has been operational since 1999. Montez highlighted that Chandra’s PR shows consistent success rates as between male and female PIs over the years.

Andrea Mejías spotlighted the Chilean Telescope Allocation Committee (CNTAC), responsible for allocating telescope time within Chile to a community of around 500 astronomers. The systematic structure of CNTAC ensures the optimal allocation of resources for these researchers.

Concluding the session, Vincent Lariviere gave a presentation on deceptive publishers and underscored the dark side of the academic publishing world. As publishing garners increased significance in research evaluations, predatory publishers exploiting the ‘publish or perish’ culture have emerged. Instances like the acceptance of a fake paper by most journals on a known predatory list and the dubious activities of some publishers were highlighted. Ethical publishing practices were advocated as a solution to countering these deceitful strategies.

In essence, this workshop session provided a holistic view of the various PR systems in place across diverse observatories, underscoring the continuous evolution, challenges and best practices in the field.

Remarks on the discussion session

In the discussion focusing on its fundamental principles we considered the multiple crucial purposes that PR serves in the scientific community. Firstly, it establishes trust between scientists and the general public, who fund scientific research, by ensuring that rigorous scrutiny is applied to research findings. This trust is essential for maintaining public support and credibility. Secondly, PR acts as a self-governance tool, upholding the quality and integrity of scientific work. It promotes transparency, accountability, and adherence to ethical standards. Furthermore, PR enhances the exchange of ideas and knowledge within the scientific community. It allows experts to critique and suggest improvements, ultimately elevating the quality of research. PR also facilitates the injection of fresh perspectives and novel ideas from diverse backgrounds, fostering innovation and interdisciplinarity. It aids in the allocation of limited resources like funding and telescope time, ensuring fair distribution. Despite its many shortcomings, the participants agreed that PR needs an evolution not a revolution.

Discussion of bias in PR not only covered the common topics of gender and racial diversity but also focused on the many unseen hurdles of the PR process. One major discussion point was that there remains a traditional bias in PR towards native English speakers, potentially disadvantaging non-native speaker researchers. One proposed solution included using structured proposal documents with templates to standardise and streamline proposal writing, minimising prose and highlighting ideas. As another way to mitigate this bias, visualisations were recognised as a valuable tool that transcends language barriers. Visualisations, being inherently language agnostic, offer a universally understandable means of conveying complex ideas, promoting better comprehension, and facilitating the assessment of proposals by reviewers from diverse linguistic backgrounds. Another key issue addressed was the regional and cultural variations in argument construction, particularly relevant in more isolated astronomy communities where common proposal writing practices may not be universally taught, especially to postdocs and graduate students.

The session also explored strategies for instigating change within the PR process, debating whether it’s more effective to encourage proposers to drive change from within the system or to push for systemic changes externally. The consensus leaned towards the necessity for both approaches to ensure a fair and effective PR system.

Participants exchanged views on the effect of the panel discussions in PR. Evaluation agreement among different people generally increases after panel discussions, but not necessarily towards accuracy. On the one hand, panel discussions allow reviewers to share expertise and correct potential misunderstandings. Being exposed to the evaluations of other reviewers can also be beneficial in improving the way reviews evaluate. On the other hand, people change their minds during panel discussions, feeling a need to conform, or when being challenged, or in confrontations with prestigious names. Biases and psychological aspects of panel discussions are hard to quantify.

Another topic discussed was the effect of dual-anonymous PR and its perception in the community. One strong advantage of dual anonymisation is that it reduces the biases in the evaluation, for example against less established researchers and those from underrepresented minorities. Biases are not completely removed though. Dual anonymisation allows reviewers to focus purely on science, rather than on personal information. On the other hand, it is sometimes hard to reach full anonymity, especially in small communities. Anonymisation is at odds with the concept of open science, where both reviewers and applicants are openly known. A two-step approach, where science only is evaluated in the first place and information on the applicants is disclosed later, could be feasible and beneficial in different fields.

Workshop demographics

The workshop saw an impressive turnout, with a total of 173 registered attendees. Among them, 46 were present in person, while 127 opted for remote participation. However, from the online group, on average 30 participants were consistently active throughout the workshop sessions. The gender distribution was relatively balanced, with 73 females, 88 males, and 12 who preferred not to specify. Breaking it down by career level, there were 111 staff members, 24 postdocs, 17 students, and 21 in the Other category. The workshop featured 34 presentations. These statistics showcase a broad spectrum of attendees, underscoring the widespread interest in the workshop's theme and content.

Concluding remarks

The Peer Review Under Review workshop was a landmark event in the assessment of PR systems within the astronomical community. The assembly of diverse experts cast a critical eye over current practices, noting challenges in managing the burgeoning volume of research, inherent biases, and the adaptability of systems in today's digital age. Throughout the sessions, there was a clear call for innovation, increased efficiency and inclusivity. Discussions ranged from the utilisation of AI and machine learning in paper evaluations, the role of chance in scientific discovery and funding, to case studies of various observatories and their unique PR systems. A particular emphasis was placed on the importance of diversity, equity, and inclusion in the PR process. Moreover, the emergence of predatory publishing underscored the need for ethical practices.

Other points concerning possible future improvements in the PR process were discussed. These included: reviewer training, motivation and awards; a more structured PR to minimise subjectivity; the possibility of making the reviews available to the readers, particularly in the context of open science; a more open and collaborative approach to PR (for example starting from preprints). Finally, the challenge posed by the rapidly growing scientific production was considered, in the context of PR sustainability and costs for society. AI tools may help to cope with this important problem, possibly providing a viable way of running a pre-screening.

The workshop[1] with all its contributions (available online via Zenodo[2]) was a clarion call for the evolution of PR, ensuring the quality, efficiency and fairness of future scientific research.

It is now the task of all those directly involved in PR to continue the discussions and to rise to the challenges that were identified, all this for more equitable, fair and effective review systems in the near future.

Acknowledgements

We extend our heartfelt gratitude to ESO for their generous financial support and essential assistance, which were pivotal in the successful execution of this workshop. Additionally, we would like to acknowledge the invaluable support provided by ESO's IT department, whose expertise and dedication played a crucial role in facilitating the smooth operation of the event. Finally, we are grateful for the valuable assistance offered by OpenAI's language model, ChatGPT.

References

Cole, S., Cole, J. R. & Simon, G. A. 1981, Science, 214, 881

Links

1. Workshop webpage: https://www.eso.org/sci/meetings/2023/PRUR.html
2. Workshop contributions: https://zenodo.org/communities/peerreview23

P. Horálek/ESO

All of ESO's observatories are based in Chile, but the organisation's headquarters, and the newest exciting addition, sits in Garching, a small city near Munich in Germany. This image shows a striking and unusual view of this new member of the ESO family — the ESO Supernova Planetarium & Visitor Centre.

DOI: 10.18727/0722-6691/5356

Report on the ESO workshop

Coordinated Surveys of the Southern Sky

held at ESO Headquarters, Garching, Germany and online, 27 February – 3 March 2023

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How can two major organisations dedicated to ground-based astronomy work together to maximise the science impact of their astronomical surveys? This was the topic for the Coordinated Surveys of the Southern Sky symposium, jointly organised by ESO and the Square Kilometre Array Observatory between 27 February and 3 March 2023. The aims of the symposium were to raise awareness across the respective communities of survey capabilities and to build liaisons in preparation for synergetic surveys, as well as for multi-wavelength follow-up programmes.

Introduction

More than 200 participants gathered, in person at ESO's headquarters and online, between 27 February and 3 March 2023, for the Coordinated Surveys of the Southern Sky symposium, jointly organised by ESO and the Square Kilometre Array Observatory (SKAO). The aim of the symposium was to plan how to get the most from surveys conducted by both organisations' facilities. To achieve this, the symposium had sessions focusing on planned surveys and current and upcoming survey facilities, including SKA pathfinder and precursor instruments as well as the SKA, and ESO's optical, near-infrared and millimetre facilities. In addition, ample time was reserved for more focused discussion sessions to create opportunities to discuss in more detail the ideas of synergies, make plans and create connections between the communities.

The SKA project originated from the desire the study neutral hydrogen emission from the earliest galaxies, requiring a collecting area of unprecedented size. Since then, the design of the SKA has evolved, and it will be able to also explore new frontiers in galaxy evolution and cosmology, cosmic magnetism, the laws of gravity, time-domain astrophysics, extraterrestrial life — and the unknown[1]. The SKAO, currently under construction, will consist of two instruments: the SKA Low, in Western Australia, observing in the 50–350 MHz frequency range, and the SKA Mid, in South Africa, with frequency bands in the 350 MHz to 15.4 GHz range. The SKAO is scheduled to begin science operations after the end of construction in 2028. The science programme for the SKAO will be determined through competitive calls for time allocation proposals from the scientific community. It is foreseen that the majority of the telescope time will go towards Key Science Projects: large observational programs, running for several years. In addition to the SKA itself, several currently operational SKA precursors and pathfinder facilities (MeerKAT, ASKAP, LOFAR, and MWA) were covered in detail at the symposium.

On the ESO side, comprehensive overviews of ESO's current facilities were presented at the symposium. Emphasis was put on upcoming instrumentation that is of particular interest for synergetic survey observations. The new Multi-Object Optical and Near-infrared Spectrograph (MOONS) currently under construction for the Very Large Telescope (VLT) will provide exquisite spectroscopic capabilities across the 0.64–1.8 μm wavelength range using 1000 fibres with individual robotic positioners. The 4-metre Multi-Object Spectroscopic Telescope is a wide-field spectroscopic survey facility that is under

Figure 1. Workshop participants attending in person at ESO's headquarters.

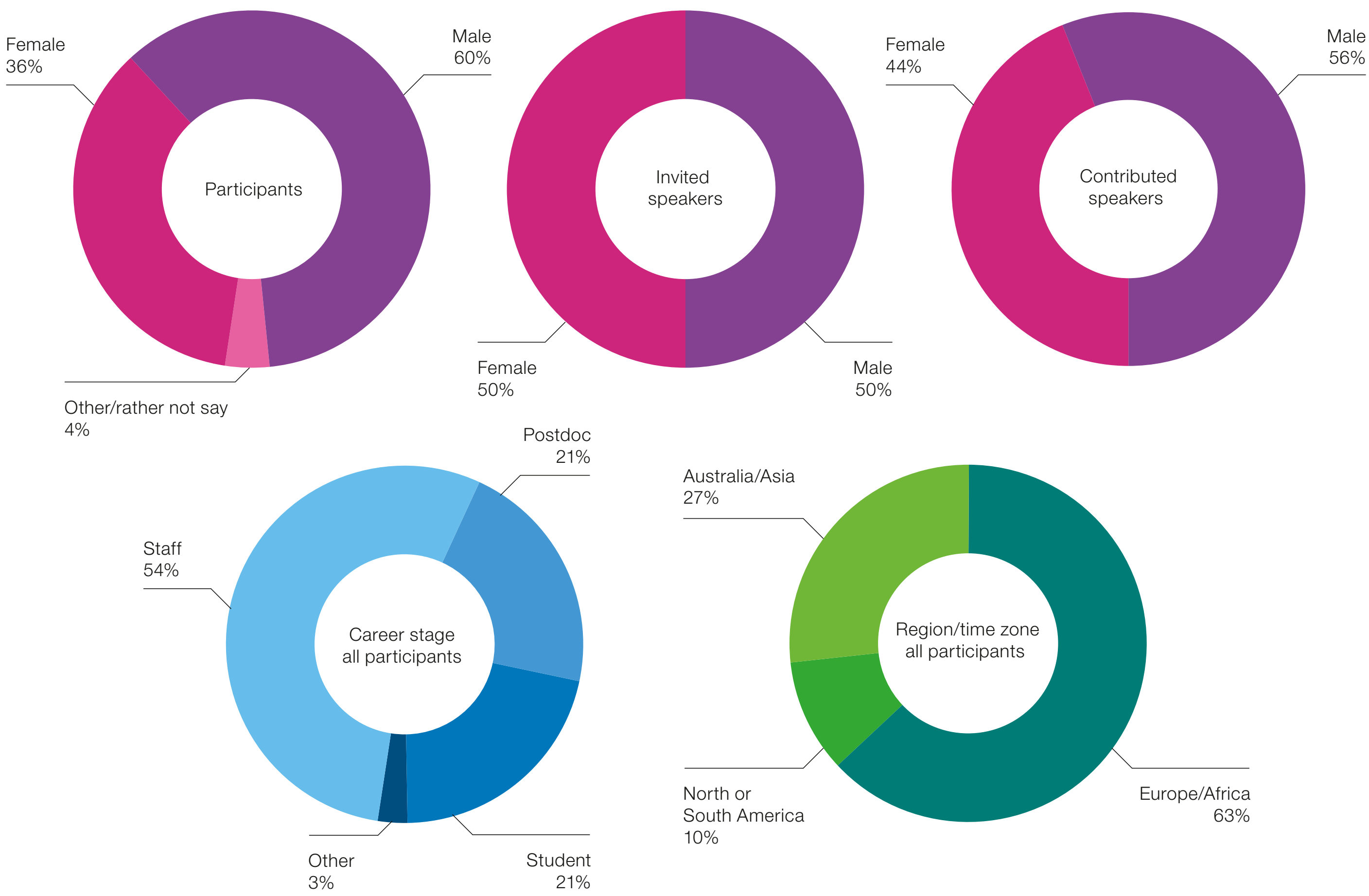

Figure 2. Demographics of workshop participants.

development for the Visible and Infrared Survey Telescope for Astronomy (VISTA) and which will be able to simultaneously obtain spectra of around 2400 objects distributed over a hexagonal field of view of 4.2 square degrees. Finally, MOSAIC will be a cutting-edge multi-object spectrograph that will use the widest possible field of view provided by ESO's Extremely Large Telescope (ELT). Another important facility for possible SKA synergies is the Atacama Large Millimeter/submillimeter Array (ALMA), which, despite its limited field of view, provides a unique view of gas and dust across the Universe, fitting quite naturally alongside deep radio observations.

Throughout the symposium, contributed presentations showcased examples of the scientific synergetic use of the above-mentioned facilities. These presentations, in addition to invited talks, addressed four intertwined themes spread over four days: 1) science within the Milky Way galaxy and our own Solar System; 2) transients and time-domain science; 3) galaxy evolution; and 4) the epoch of reionisation, cosmology and the high-redshift Universe. Following the main symposium, two half-days were reserved for more focused workshops, organised by science theme. The purpose of these workshops was to synergise the ideas presented at the symposium, forge synergies between different teams and develop plans for collaborative surveys and cross-facility follow-up programmes.

Synergies per science area

The Galaxy

The Galactic centre provides an excellent example of where multiwavelength observations are essential to capitalise on the power of the current and next generation of telescopes. The Galactic centre has already been targeted extensively with, for example, ALMA and the VLT(Interferometer), and future observations with these facilities in concert with the SKA will provide a wealth of information on its structure, the formation history, star formation etc. Other potential opportunities for synergetic science in the Galaxy include grain growth in protoplanetary discs or the physics of young stellar objects, where joint wide-field observations with MOONS and the SKA could target hundreds of objects, which then could be combined with pointed ALMA observations. Unidentified radio sources were underscored as another example, where wide-field optical follow-up with, for example, 4MOST, would assist identification.

Transients and time-domain

The SKA and its pathfinders are opening up new avenues into real-time discovery of transient events, as well as the potential to access previously inaccessible timescales. The SKA could serve as a transient discovery machine for, for instance, Fast Radio Bursts, providing targets for follow-up with ESO facilities. Multi-wavelength follow-up is critical for the characterisation of astrophysical transients and should cover a range of timescales. Immediate response times are important for reverse shocks in gamma-ray bursts, and longer timescales are needed to study source evolution with light curves, as well as for redshift measurements of extragalactic transient sources. The instruments needed for this work encompass most of ESO's facilities, providing wide-field deep imaging, spectroscopy, and high angular resolution, as well as similar capabilities on SKA's facilities including the high-time-resolution mode.

Galaxies and galaxy evolution

The discussions around this theme highlighted the importance of running optical spectroscopy surveys ahead of SKA surveys. This would avoid the need for long spectroscopic follow-up campaigns, and the availability of spectroscopic data would allow, for example, HI 21-cm stacking of the radio data. In particular, the importance of 4MOST surveys supporting SKA redshift survey campaigns was emphasised, as well as integral field unit and ALMA deep fields, which in tandem with SKA deep observations, will provide a full census of molecular, atomic and ionised gas at kiloparsec-scale spatial resolution. Joint galaxy evolution studies would benefit from a tiered approach to the identification of survey fields, ranging from a few to several thousand square degrees.

Epoch of reionisation, cosmology and high redshift

Similar arguments hold for this science area. In particular, near-infrared spectroscopy over large fields offered by MOONS and MOSAIC will provide large samples of galaxies at high redshift, which, cross-correlated with low-frequency SKA surveys, give a unique insight into galaxies at the time of cosmic reionisation. Similar synergies would enable intensity mapping used for measuring the three-dimensional structure of the early Universe. For cosmological surveys, obvious synergies exist between the 4MOST and SKA wide-field surveys.

Concluding remarks

Participants were deeply engaged in suggesting and discussing synergetic science over the course of the symposium. The examples given above are merely the beginning of what science and which coordinated observations will be possible. Those ideas will be consolidated over the next months into a publication that will be a point of reference for collaborations going forward.

To prepare optimally for future joint surveys between SKAO and ESO facilities, several points related to policy and organisation were touched upon which will require further discussion. For example, participants addressed the possibility of exploring coordinated time allocation processes to optimise the efficiency of telescope scheduling and as a means to forge collaborations early on. In addition, coordinated archival capabilities were highlighted as an area where much common effort would be beneficial. Existing Virtual Observatory infrastructure efforts and precursor datasets should be used to train and prepare for SKA datasets. Note that existing survey teams are doing a lot of preparatory work that should be built on for future infrastructure.

The workshop took place at ESO's Headquarters in Garching, and allowed virtual as well as in-person participation. The Scientific Organising Committee (SOC) was composed of Anna Bonaldi (SKAO, co-chair), Martin Zwaan (ESO, co-chair), Barbara Catinella (ICRAR/UWA), Michele Cirasuolo (ESO), Pratika Dayal (Groningen), Miroslava Dessauges (Geneva), Jan Forbrich (Hertfordshire), Jochen Liske (Hamburg), Celine Peroux (ESO), Elaine Sadler (Sydney) and Patrick Woudt (Cape Town). In total 276 participants registered for the symposium, at any time approximately 90 people attended in person, others participated online and numbers varied depending on the geographical location of the participants. The organisers ensured a balanced distribution of gender, seniority and geographical origin of the SOC members, the invited speakers, and the workshop leads (see Figure 2).

Acknowledgements

Many thanks to the Local Organising Committee, which consisted of Alžběta Opluštilová, Ellen Leitinger, Ivanna Langan, Martin Zwaan, Nelma Silva, and Simon Weng. In addition, we thank the SOC, and especially also the discussion leads of the various workshops: Mario Santo, Anna Bonaldi, Shari Breen, Rainer Schoedel, Matthew Colless, Isabella Prandoni, Ben Stappers, and Patrick Woudt.

Links

[1] SKA Science Book: https://www.dropbox.com/scl/fi/t5fuudtu1zqr6flswcbgn/SKA-Astophysics-Vol1.pdf?rlkey=4gg5vk7fngi0n9w6ft59sldnf&e=1&dl=0z

 DOI: 10.18727/0722-6691/5357

Report on the EAS Special Session

The Millimeter Transient Sky: Present Opportunities and Perspectives

Special Session held at the EAS Annual Meeting 2023 in Krakow, Poland, 10–14 July 2023

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Time-domain astronomy was identified as a key science area in the US Astro2020 Decadal Survey and is one of the active support areas of ASTRONET. Consistent with these priorities, dedicated facilities are being constructed for studying the variable sky. However, at millimeter wavelengths, only recently have such studies lifted off thanks to the advent of the Atacama Large Millimeter/submillimeter Array (ALMA), with unprecedented sensitivity, and of upgrades of other existing millimetre observatories. The advances in this field and how to overcome the associated challenges were the subject of a special session at the 2023 European Astronomical Society Annual Meeting.

Motivation

The millimetre bandpass is often thought of as being predominantly for studying cool, thermal emitters, like molecular clouds, protoplanetary discs, dust, and the cosmic microwave background (CMB). Such objects must be physically large in order to reach the brightness temperature limits of most millimetre-band facilities, and hence only weakly variable on sub-week timescales. However, the millimetre band also probes synchrotron emission and optically thin free-free emission effectively. Sources emitting via these processes often vary quickly and dramatically. The millimetre band tends to rise earlier and vary more sharply than the radio band (Figure 1), while being less susceptible to interstellar absorption and contamination from blackbody emission than the infrared band. The millimetre emission is also often quite short-lived, requiring either highly responsive Target of Opportunity (ToO) observations, or, for brighter events, very wide field coverage. Time-domain astronomy has grown immensely in the past years as wide-field surveys and sensitive time-domain follow-up facilities have been produced. It was identified as a key science area in the US Astro2020 Decadal Survey[1] and is one of the active support areas of ASTRONET[2]. At millimetre and submillimetre wavelengths, however, the field is still in its infancy. Narrow fields of view of millimetre instruments have precluded serendipitous discovery of millimetre-band transients, and operational challenges in obtaining fast triggers have hampered studies of transient events discovered at other wavelengths. With higher angular resolution, more sensitive CMB surveys, millimetre-band selection of transients has started (Guns et al., 2021) and should accelerate with projects like CMB-S4[3]. Similarly, response times for millimetre follow-up have improved considerably, and could continue to improve.

Special session SS40 at the European Astronomical Society 2023 Annual Meeting showcased recent advances in our understanding of the millimetre variable sky and allowed discussions with staff from millimetre observatories on strategies to enable time-sensitive observations via new processes and policies. The discussions clearly established that the science enabled by such rapid-response science is compelling.

Science opportunities

The session included invited and contributed talks on magnetars, Fast Radio Bursts (FRBs), gamma-ray bursts (GRBs), X-ray binaries (XRBs), pulsars, supernovae, young stars and active galactic nuclei (AGN).

Accretion processes and associated events like launching of relativistic jets in XRBs, accreting millisecond pulsars, AGN or tidal disruption events are undoubtedly one of the main time-domain topics in the millimetre. Precise timing of multi-wavelength variability including flares allows the relative position of emitting regions along the jet to be established, leading to a better understanding of jet propagation and the role of shocks by constraining regions of energisation (for example, Abdo et al., 2010; Tetarenko et al., 2021) and ultimately allowing important jet properties like collimation angle and speed to be determined. Variability of the magnetic field strength and geometry via evolution of the degree of polarisation (Hughes et al., 2023; Myserlis et al., 2018) and of the jet frequency break from optically thick to thin emission (observed in XRBs in real time during accretion outbursts; Russell et al., 2014) are crucial to further investigate how jets are launched and quenched. Finally, exciting science opportunities in this field are linked to the availability of Very Long Baseline Interferometry (VLBI) capabilities, which have already revealed, for example, a rapidly changing (minutes to hours) jet orientation in a stellar-mass black hole at lower frequencies (Miller-Jones et al., 2019).

Outflows in general are one of the products of explosions, stellar collapse or gravitational wave mergers. Studies of the millimetre emission including polarisation of well-known transients like GRBs or recently discovered ones like Fast Blue Optical Transients shortly after the event are crucial to disentangling the different components of emission, such as reverse and forward shocks in GRBs (Laskar et al., 2018). Spectral line observations provide the opportunity to identify the host galaxies of these events, thanks to the presence of molecular and cooling lines from the interstellar medium at all redshifts in the millimetre band (for example, de Ugarte Postigo et al., 2020).

Finally, accretion processes are also at the core of variability around young stars, one of the object classes mostly studied at (sub-)millimetre wavelengths given the presence of thermal dust (from the outer disc and the envelope), free-free emission from the jet and possible gyro-synchrotron emission from magnetic reconnection events which are bright in this wavelength regime (Wielgus et al., 2022). Time-resolved observations on timescales from minutes to years (for example, Fischer et al., 2023) are needed to explore circumstellar geometry and physical structure following heating from accretion (Lee et al., 2020) or changes in disc chemistry following X-ray flares (Cleeves et al., 2017), while longer-cadence monitoring is needed to understand binary interactions between magnetospheres or winds from young stars (for example, Salter et al., 2010).

Challenges

The discussion panel at the special session was composed of Liz Humphreys (chair, ALMA), Adam Hincks (Atacama Cosmology Telescope), Garret Keating (Submillimeter Array [SMA]) and Venkatessh Ramakrishnan (new generation Event Horizon Telescope).

A series of challenges for millimetre time-domain studies were identified, with some being common to all wavelengths (Middleton et al., 2017) and a few particular to millimetre observatories. In what follows we discuss the latter together with potential mitigations.

Obtaining observing time. The rarity of some of the transient phenomena and the need to obtain multi-wavelength observations imply that resources of the scientific teams are typically spread over many observatories, resulting in only few proposals per wavelength range and class of objects, often without a millimetre expert on their teams. For example, while GRBs are a popular astronomical topic, only a handful of proposals are received at ALMA per cycle. This often results in diverse science being classified under ‘time-domain’ and being evaluated by reviewers with expertise in a wide range of classes of objects, and perhaps even competing against each other in distributed review processes, making it more challenging to obtain observing time. This was recognised as a severe problem for highly oversubscribed observatories like ALMA. Soliciting observations of rare events under Director’s Discretionary Time is instead positively regarded by medium-size telescopes like the SMA in the context of expanding their scientific areas to novel topics.

Potential mitigations include:
– Ensure that experts evaluate the proposals by defining the keywords in a more flexible way and widening the range of keywords.
– When possible, submit first proposals to medium-size observatories as pilots.
– Perform observations that show the capabilities of new modes to catch the attention of the community.
– Use the possibilities offered by some observatories to request observing time in two or more observatories via Joint Proposals (for example ALMA–James Webb Space Telescope, ALMA–Very Large Array or ALMA–Very Large Telescope) and have the coordination done by the observatories to reduce overheads. Given the prevalence of high-energy emission among millimetre transients, some consideration should be given to including joint calls with X-ray observatories.
– Memoranda of Understanding can help boost specific nascent fields, for example correlating with AGN/neutrino events, gravitational waves or pulsar timing arrays.
– Provide observatory support for preparing proposals and setting up the observations.

Understanding of constraints and scheduling by the observatories. Besides fast reaction times for ToOs, some time-domain science cases require monitoring over timescales longer than the usual yearly cycle of proposals. Others require multi-observatory coordination with rapid response times. These constraints add to other constraints inherent in the millimetre wavelength regime (for example, the need for superb weather for high-frequency submillimetre observations) or observational technique (for example, the need for a specific array configuration for interferometric observations). While time-domain users are often sensitive to the need to relax some constraints when the time constraint is fulfilled, this is not always allowed by observatory policies (for example, changing the observing frequency if the weather is not good enough for the originally requested frequency).

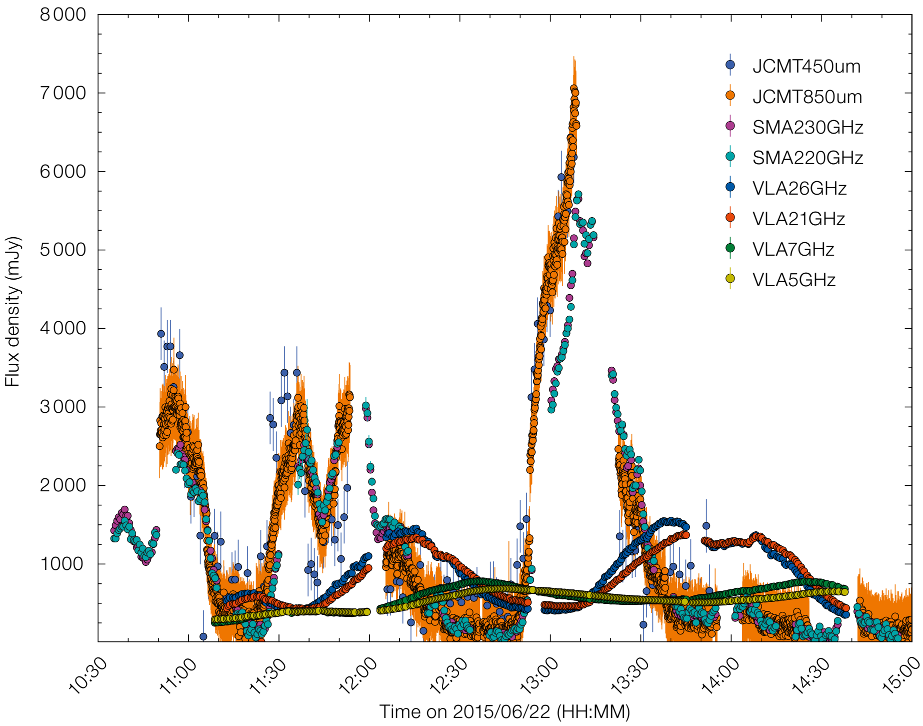

Figure 1. Simultaneous radio through submillimetre lightcurves of the black hole XRB V404 Cygni during the most active phase of its June 2015 outburst. These lightcurves sample the brightest flares at these frequencies over the entire outburst. All lightcurves are sampled at the finest time resolution possible, limited only by the correlator dump time (and the sensitivity for James Clerk Maxwell Telescope [JCMT] data). The Very Large Array lightcurves have two-second time bins, the SMA lightcurves have 30-second time bins, the JCMT Submillimetre Common-User Bolometer Array 2 (SCUBA-2) 350-GHz (850-μm) lightcurve has five-second time bins, and the JCMT SCUBA-2 666-GHz (450-μm) lightcurve has 60-second time bins. The millimetre/submillimetre regime samples a much more extreme view of the flaring activity than the radio regime, with detailed substructure detected only in the millimetre/submillimetre lightcurves. (From Tetarenko et al., 2017, reproduced with the permission of the author).

Potential mitigations include:
– Explore the possibility of carrying over proposals with a low triggering probability over two or more cycles.
– Offer the possibility to relax constraints other than the time-related one at the moment of triggering to enhance observability.
– Automate procedures as far as possible and have a contact person at the observatory to iterate with the user on scheduling possibilities or array availability upon triggering to enable fast reactions.
– Offer multi-cycle proposals for long timescales monitoring programmes.
– Offer ToO capabilities for phased-array and VLBI modes.

Observing cadence and scheduling priority. Given the increase in time-domain observations, establishing adequate observing priorities is crucial, especially for events requiring high-cadence monitoring for a few days or weeks after the trigger.

Potential mitigations include:
– Request estimates of triggering probability from the users so that the observatory can establish priorities relative to other observations based on the rarity of events.
– Explore the use of small arrays (like the Atacama Compact Array in ALMA) for localisation and high-cadence monitoring of bright transients.

Time sampling. A few of the phenomena can only be studied with sub-second (nanosecond to millisecond) time sampling. While fast time sampling is not offered by many millimetre observatories, it is often technically possible and can be enabled with minor operational changes. This is key, for example, for studies of pulsars, such as that of Torne et al. (2021), who performed the first survey unaffected by scattering and therefore unbiased in population coverage at the Galactic centre at 2 and 3 millimetres via time series with 100-microsecond resolution.

Multi-frequency sub-arraying capability raises the possibility of using time-correlation techniques for phenomena with second and subsecond variability, including the Sun.

Real-time light curves. Especially for wide-field and all-sky survey millimetre telescopes like the upcoming Simons Observatory[4], making hourly to daily light curves accessible to the community could be a game-changer for the discovery of millimetre transients. Such light curves must be accompanied by algorithms matching variable sources to multi-wavelength catalogues and notifications to the community, ideally in a standard format agreed by the community and readable by automatic text processing tools.

Real-time data delivery. Monitoring observations of transients (for example of a GRB afterglow) over the days and weeks following the first trigger depend on the brightness and evolution of the event, both often difficult to predict. In this context, 'real time' data processing for quick look data, including for phased-array and VLBI modes, and communication to PIs are crucial to avoid wasting observatory time.

Technical issues. For long-timescale monitoring, flux calibration uncertainties must be well known and as small as possible (for example, less than a percent for stellar occultations). Moreover, interferometric monitoring spanning months or years could be impacted by changes in array configuration leading to missing flux in extended configurations. Finally, the calibration accuracy needed for polarimetry, a powerful tool for studies of millimetre variable objects, is often not sufficient for the low (less than a percent in some cases) levels of polarisation.

Outlook

The enormous potential of time-domain studies in the millimetre has only recently been unveiled. However, the characteristics inherent in such studies make it necessary to implement some changes in the operation of millimetre telescopes to fully exploit this potential. These changes are pressing in light of upcoming facilities like Vera C. Rubin Observatory, expected to discover millions of transients every night, but also of planned sensitive, wide-angle, facilities at millimetre wavelengths like AtLAST[5] or CMB-S4, which will open up the millimetre transient discovery space.

Acknowledgements

We are indebted to the Scientific Organising Committee (SOC), the invited and contributed speakers and the discussion panel for sharing their insights and vision for opening the millimetre window to the variable sky.

SOC: María Díaz Trigo (ESO, Germany), Thomas Maccarone (Texas Tech University, USA), Alex Tetarenko (University of Lethbridge, Canada), Rob Fender (Oxford University, UK), Doug Johnstone (NRC-Herzberg, Canada), Venkatessh Ramakrishnan (University of Turku, Finland), Pablo Torne (IRAM, Spain), Susanna Vergani (Paris Observatory, France)

Invited speakers: Agnes Kospal (Konkoly Observatory, Hungary), Tom Russell (INAF, Palermo, Italy), Ioannis Myserlis (IRAM, Spain) and Antonio de Ugarte Postigo (Côte d'Azur Observatory, France)

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2 ASTRONET webpage: https://www.astronet-eu.org/
3 CMB-S4 webpage: https://cmb-s4.org/
4 Simons Observatory webpage: https://simonsobservatory.org/
5 AtLAST webpage: https://www.atlast.uio.no/

DOI: 10.18727/0722-6691/5358

Report on the Australia–ESO conference

Galaxy Transformation Across Space and Time — the Third Australia–ESO meeting

held at the Australian Academy of Science, Canbera, Australia, 4–8 September 2023

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Trevor Mendel [1,2]

1 Research School of Astronomy and Astrophysics, Australian National University
2 Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions

We report on the third joint Australia–ESO conference since the commencement of the strategic partnership between Australia and ESO. The conference was supported by ESO, the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), the Australian National University, and the International Centre for Radio Astronomy Research. The meeting focused on new results from ongoing surveys and simulations of galaxies and their evolution. The motivations for upcoming facilities such as the Multi-conjugate adaptive optics-Assisted Visible Imager and Spectrograph (MAVIS), the Square Kilometre Array (SKA), Vera C. Rubin Observatory, and the Wide-field Spectroscopic Telescope and the new science opportunities and collaborations that they will enable were discussed. The meeting achieved a gender-balanced participant list and strove to provide an inclusive environment. It was a pleasure to share science again in person since the last joint Australia–ESO conference in February 2020. While there was some flexibility for inclusion purposes, the meeting prioritised in-person attendance with only five remote talks.

Motivation

With new capabilities enabling highly-resolved multi-wavelength investigations of gas and stars in local galaxies (for example, the Physics at High Angular resolution in Nearby GalaxieS [PHANGS], Generalising Edge-on galaxies and their Chemical bimodalities, Kinematics and Outflows out to Solar environments [GECKOS], MUSE and ALMA Unveiling the Virgo Environment [MAUVE], and Fornax 3D surveys), it is now possible to disentangle detailed star formation and assembly histories for a wider variety of galaxy types. Simultaneously, surveys pushing resolved observations to earlier times are providing important constraints on the evolution and transformation of dynamics and chemical distributions (for example, the Middle Ages Galaxy Properties with Integral Field Spectroscopy [MAGPI], MUSE gAlaxy Groups In Cosmos [MAGIC], and Large Early Galaxy Astrophysics Census [LEGA-C] surveys). Together these approaches have the power to discern complex assembly histories over the last 7 Gyrs. Simulations suggest that most of the morphological and kinematic evolution is expected to have occurred over the same epoch, but the exact timing and nature of the transformations are debated.

A key player in the redistribution of gas and stars likely comes from galaxy-galaxy interactions, typically in the group environment. Upcoming surveys obtaining millions of galaxy spectra at high densities (for example, using ESO's 4-metre Multi-Object Spectrograph and Telescope [4MOST] and Multi-Object Optical and Near-infrared Spectrograph [MOONS], NOIRLab's Dark Energy Spectroscopic Instrument [DESI], and the Subaru Telescope's Prime Focus Spectrograph [PFS]) combined with deep photometry (from, for example, Rubin Observatory and the Euclid and Nancy Grace Roman space missions) over large areas of sky will allow the environmental metrics necessary to make these connections to be measured consistently out to $z \sim 1$. Tying stellar tracers with gas tracers from the Australian SKA Pathfinder [ASKAP], MeerKAT and the SKA will be essential to disentangling the role of different processes in the group and cluster environments. The meeting provided a forum to explore the synergies between the different theoretical and observational datasets relating to the role

Figure 1. Participants engaging in science discussions during teatime at the Australian Academy of Science.

of environment on quenching, star formation histories, and angular momentum. The meeting was designed around science questions rather than techniques in order to promote a more integrated discussion of simulations and multiwavelength (including radio) results.
The conference[1] was divided into five major themes used to focus the topics presented each day:
– What is the environmental impact on redistributing angular momentum?
– How do we connect galaxy populations across epochs?
– How will new facilities address the questions surrounding how galaxies transform?
– How does the environment shape the star-formation history of galaxies?
– How do stellar and AGN feedback regulate the gas-star formation cycle at $z \sim 0$?

Key scientific results discussed during the meeting included recent breakthroughs combining deep optical spectroscopy from the Multi-Unit Spectroscopic Explorer (MUSE) and the William Herschel Telescope Enhanced Area Velocity Explorer (WEAVE) with data from ASKAP, MeerKAT, the Atacama Large Millimeter/submillimeter Array (ALMA) and the Low-Frequency Array (LOFAR) to study gas flows from parsec to megaparsec scales. Along these lines, the GECKOS and MAUVE surveys in particular showed beautiful images revealing the complexity of these gas flows around nearby galaxies. Such detailed multiwavelength studies help us better understand the relationship between star-forming regions, the galaxies that host them, and the large-scale environments that they live in. Several talks also emphasised the key role that the James Webb Space Telescope (JWST) has to play across a broad range of redshifts, both extending the study of local galaxies into the mid-infrared and enabling deep continuum observations of galaxies in the distant Universe.

Environment is an inherently broad term in galaxy evolution. Participants presented results on the role of environment from galaxy pairs on kiloparsec scale to the megaparsec scale of voids and filaments. We heard about results indicating that the cosmic web and its complex interplay with galaxies are multi-scale.

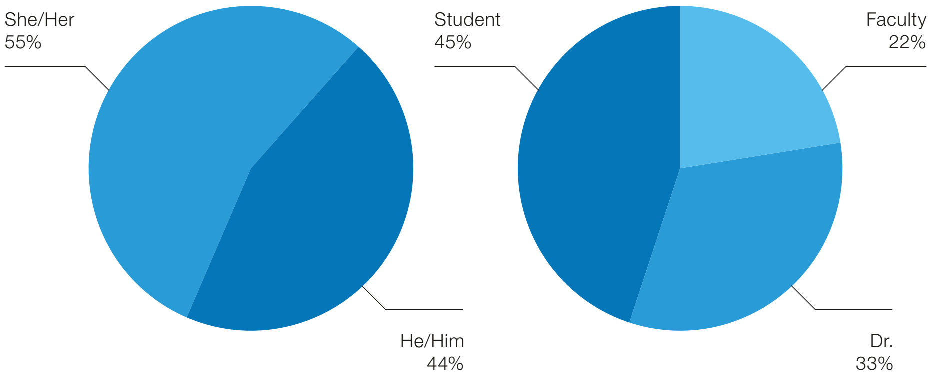

Figure 2. Distributions of gender (left) and seniority (right) of participatants including invited and contributed talks, poster presentations, and attendees. Gender statistics were inferred from participant provided pronouns. The seniority label 'Dr.' includes postdocs as well as staff not in a typical University setting.

Results testing Tidal Torque Theory in the local Universe highlight that more work is needed to find correlations between angular momentum and the ancient cosmic web. Future facilities densely mapping out large-scale structure to cosmic noon will add constraints on the timescale of galaxy spin decoupling from the cosmic web and the processes responsible. During the conference the MAGPI team showcased the first year of major results including that most of the dynamical evolution between $z \sim 0.8$ and $z \sim 0$ must happen before $z \sim 0.35$.

Connecting galaxies across epochs becomes an important exercise to track the changes of galaxy spin, morphology, and star formation. Limitations in the different approaches were highlighted, along with possible ways forward including using joint observation inference as well as improvements in simulations. Recent simulation results show that connecting galaxy environment across time may be more complex than assumed. While the largest overdensities at $z \sim 4$ are often theorised to be the progenitors of massive Coma-like clusters, simulations show that a large fraction of locally overdense regions in the early Universe may quickly consume their gas and become quiescent early owing to being underdense on larger scales. This was supported by some preliminary observational results presented from the One-hundred-square-degree DECam Imaging in Narrowbands (ODIN) survey in the Cosmic Evolution Survey (COSMOS) field.

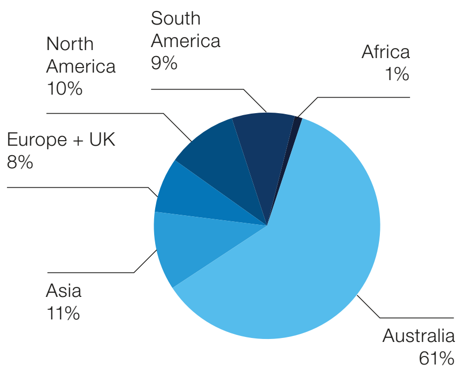

Figure 3. Distribution by country of current study/employment of the 90 participants.

The varying role of star formation and active galactic nucleus (AGN) feedback in regulating the gas available to galaxies was central to numerous discussions throughout the meeting. Data from the GECKOS and the Deep near-UV observations of Entrained gas in Turbulent galaxies (DUVET) surveys in particular were used to highlight the complex, spatially-extended nature of outflowing material in local galaxies, which in some cases could be directly imaged out to several tens of kiloparsecs. These results for nearby galaxies were complemented by JWST data showing that large reservoirs of outflowing neutral gas, likely driven by AGN, may play a key role in quenching galaxies at early epochs.

A recurring topic across the five themes of the meeting was the importance of scale and the interplay of physics from the scale of the cosmic web (hundreds of megaparsecs) to the scale of star-formation (parsecs). There is no one scale that captures how galaxies transform over cosmic time — processes such as feedback are inherently multi-scale. It is clear that a more complete observational picture of galaxies will soon be available from new surveys and facilities but it was noted that new simulations were needed at all scales, including even larger boxes to capture rare overdensities as well as higher resolution to include cloud-scale gas physics.

Demographics and inclusivity

One advantage of large multinational collaborations like the ESO–Australia partnership and the international galaxy evolution community is the diversity of experience and backgrounds. As has been noted in previous articles about ESO meetings (Zafar, De Breuck & Arnaboldi, 2019; Lagos, Robotham & De Breuck, 2020), tackling unconscious bias when organising a science meeting is important for achieving a diverse range of ideas and perspectives. We have followed the guidelines of previous meetings and from supporting organisations to (1) anonymise contributed abstracts, (2) ask the SOC to declare conflicts of interest, (3) anonymise SOC votes, and (4) have a multinational and gender-balanced set of invited speakers. Opting for longer talks, the conference had 10 invited talks, 55 contributed talks, and 10 poster presentations. The adopted guidelines naturally gave rise to a balanced meeting across gender, seniority, and country (see Figures 2 and 3). This is the first meeting in this series that had more female than male participants.

However, the responsibility to hold an inclusive meeting does not stop at the participation list. The Local Organising Committee took some additional measures to ensure participation from all demographics. This included announcing a Code of Conduct for the meeting during the welcome talk and posting it on the conference webpage where it could easily be referenced. The main purpose of the Code of Conduct is to remind participants to behave professionally and communicate in a respectful manner to all.

The meeting was opened by Aunty Violet Sheridan, a local Ngunnawal Elder who led an Acknowledgement of Country — a custom adopted throughout Australia to show our respect for the land and its traditional owners. A dedicated prayer room was made available to participants throughout the meeting. To encourage participation by the younger cohort, all session chairs were asked to take questions from students and early career researchers first before opening the floor to questions from the whole audience. This resulted in an engaging discussion between speaker and audience after most of the talks.

Future

Since the start of the 10-year ESO–Australia strategic partnership (2017–2027) there have been three joint ESO–Australia workshops on galaxy evolution (Zafar, De Breuck & Arnaboldi, 2019; Lagos, Robotham & De Breuck, 2020), held in Australia in 2019, 2020, and 2023. It has been a fruitful collaboration that we hope to continue. We were happy to welcome Australian government officials to the Wednesday session to share the benefits of the partnership. Scientifically, from this meeting it is clear that multiple tracers of stellar and gas properties across diverse phases and scales are required to understand the processes that transform galaxies. This necessitates a multi-wavelength, multi-facility approach. We look forward to continued collaboration with ESO members and projects with a focus on ESO-SKA connections.

Acknowledgements

We thank the sponsors of our conference: ESO, ASTRO 3D, the Australian National University, and the International Centre for Radio Astronomy Research. They allowed us to keep the conference fee relatively low by Australian standards and allowed us to provide travel grants to some students and invited speakers.

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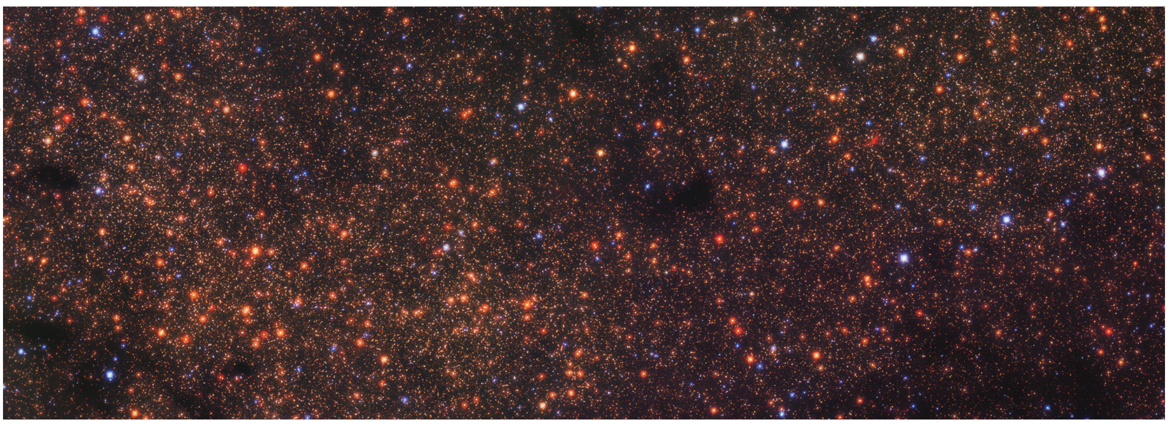
[1] Conference webpage: https://www.mso.anu.edu.au/~jtmendel/galtrans2023/



Hundreds of thousands of stars are contained in this infrared image of Sagittarius C, a region near the centre of the Milky Way. This image was taken with ESO's Very Large Telescope (VLT) in the Chilean Atacama Desert.

DOI: 10.18727/0722-6691/5359

Report on the ESO workshop

Two in a Million — The Interplay Between Binaries and Star Clusters

held at ESO Headquarters, Garching, Germany and online, 11–15 September 2023

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Julia Bodensteiner[2]

[1] Liverpool John Moores University, UK
[2] ESO

Figure 1. Conference photo in front of the ESO Supernova Planetarium & Visitor Centre.

A substantial fraction of cosmic star formation happens in star clusters, and the binary populations therein are shaped by interactions amongst themselves and with other cluster stars. The intricate interplay of star clusters and the binary stars they host was the topic of this workshop, which brought together about 150 scientists working on four cornerstones of modern astrophysics: star formation, stellar evolution, cluster dynamics, and gravitational waves. As well as invited reviews and contributed talks, the scientific programme offered breakout sessions focused on various practical skills linked to the workshop theme. Informal poster-viewing sessions concluded the session days and offered the opportunity for extended discussions about recent results as well as future instruments.

Rationale

Each binary in a star cluster will evolve through a multitude of interactions with other cluster members. These interactions strongly alter the primordial populations via binary disruption, flyby and exchange interactions, or the Kozai-Lidov mechanism (Kozai, 1962; Lidov, 1962), and result in systems that are endemic to clusters such as dynamically-formed binary black holes or low-mass stars orbiting degenerate companions. The detection and characterisation of the latter hold crucial information about the kick velocities resulting from supernova explosions, a major unknown limiting our capabilities to understand the growing number of gravitational wave detections.

Remarkably, star clusters also provide a unique window through which to study a multitude of phenomena linked to binary stars in a controlled environment, since the ages, metallicities, and masses of cluster members are usually well known. Given that, star clusters play a key role in improving our understanding of post-interaction products, like blue stragglers, stripped stars, or classical Be stars. Different formation mechanisms for these objects make predictions that can best be tested in clusters, such as the stellar-merger or mass-transfer scenarios proposed for blue straggler formation.

Binary stars also have a crucial impact on the evolution of clusters, and act as reservoirs that balance the energy budget of their hosts, closely linking the lifetime of a cluster to its binary population. Binaries reverse and moderate the core collapse of long-lived clusters, while few-body interactions involving binaries efficiently eject cluster members from their hosts. Some of the open questions in our understanding of cluster evolution, like the origin of the bimodal spin distributions found in young open clusters or the multiple-populations phenomenon observed in old globular clusters, have been linked to binary stars.

The current Very Large Telescope (VLT) instrumentation, particularly the Fibre Large Array Multi Element Spectrograph (FLAMES) and the Multi Unit Spectroscopic Explorer (MUSE), has allowed significant advances in our understanding of how binary evolution impacts star clusters and vice versa. The workshop offered an opportunity to review these successes and to plan ahead for new and upcoming instruments, like the Enhanced Resolution Imager and Spectrograph (ERIS) and the Multi-Object Optical and Near-infrared Spectrograph (MOONS) on the VLT, or ESO's Extremely Large Telescope (ELT) with its groundbreaking set of instruments, which will significantly boost our ability to study stellar populations in clusters.

Programme

The scientific talks during the week were structured according to the four scientific pillars on which the workshop rested[1]. Following the typical evolutionary sequence, the programme started on Monday with sessions on star and cluster formation, while Tuesday was largely dedicated to the binary populations in young star clusters. After the sessions on interacting binary stars on Tuesday afternoon and Wednesday, Thursday was dedicated to ancient globular clusters and their binaries, before the workshop concluded on Friday with a series of talks presenting new results on the possible star–cluster links of binary black hole mergers detected via gravitational waves, both from an observational and a theoretical point of view. Additionally, each day featured one talk about instrumentation, presenting either current instrumentation such as LIGO/VIRGO/KAGRA gravitational wave detectors, introducing new instruments such as VLT/MOONS, or highlighting the capabilities of the ELT.

Recurring themes throughout the week included the strong dependency of multiplicity properties on stellar mass, the

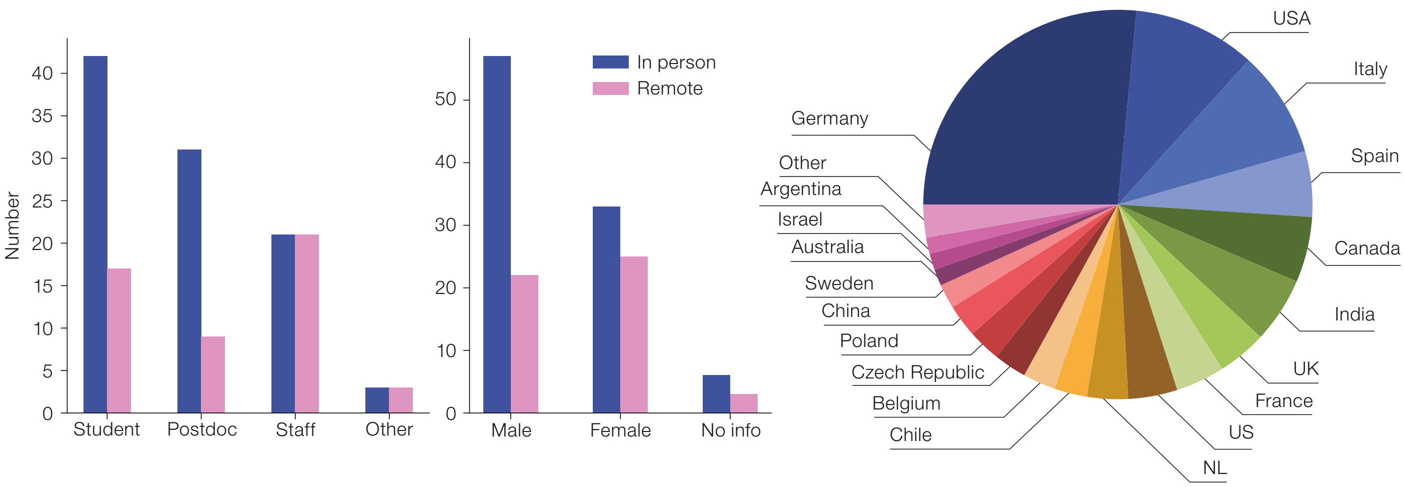

Figure 2. Demographic distributions of the career stage (left) and gender (middle) of the participants, split up into in-person (blue) and remote (pink) participants. Right: Overview of the home countries of all participants.

importance of interaction products in explaining the colour-magnitude diagrams of young star clusters, the power of the Gaia spacecraft in studying binaries in nearby star clusters as well as runaway stars, and the necessity of detailed comparisons between models and observations to understand the binary populations inside star clusters. For further details, we refer the interested reader to the presentation slides, made available by the workshop participants on Zenodo[2].

In addition to the invited and contributed talks, two slots for breakout sessions were included in the programme and took place on Tuesday and Thursday afternoon. Those were filled by the participants themselves with interactive sessions, more in-depth discussions, and hands-on tutorials covering many different skills. Those included, for example, a hands-on session about machine learning and its application to star clusters, a discussion session about potential new instruments for the VLT, the status of ELT instrumentation, and ideas for new telescopes beyond the ELT, as well as a career-planning session particularly targeting junior scientists, in which more senior scientists offered tips, tricks and experiences on how to navigate through an academic career.

Two poster sessions were organised in the evenings, with typical Bavarian refreshments, which enabled participants to inspect and discuss the posters and to interact in a more informal setting.

Demographics

Overall, almost 150 scientists participated in the conference, of whom roughly two thirds attended in person, the remainder joining online. In addition to bringing together scientists from different research fields, the Scientific Organising Committee (SOC) and the Local Organising Committee (LOC) sought fair representation from the communities in all possible aspects. In particular, the conference targeted early-career scientists, who could for example apply for travel support. As shown in Figure 2, the overall participation of early-career scientists was high, with almost 70% of all participants being either students or postdocs. A majority of those attended the conference in person.

While the ratio between male and female participants was roughly 60/40, the ratio between male and female speakers was approximately 50/50. When selecting the invited talks, the SOC strove to have a similar number of female and male speakers, and to achieve fair distribution between senior and junior speakers.

Overall, there were participants from 22 different countries from five different continents. The fractions of participants coming from individual countries can be seen in the right panel of Figure 2.

Outlook

All in all, the conference was a great success, fulfilling the goal of bringing together scientists from many different communities and providing a platform for the exchange of recent findings and new ideas, in particular for the younger generation. During the conference summary, which was prepared and presented by a group of PhD students who volunteered for this task[3], it was suggested that a ‘Three in a million’ conference be hosted at ESO in 10 years from now — a promising idea that will hopefully be seized on by one of our younger colleagues.

Acknowledgements

We would like to thank all participants, in person and remote, for their active participation in the conference, which was crucial in making it so interesting and diverse. We would further like to thank our SOC and LOC members for their active and energetic support. A special thanks goes to Denisa Tako for her endless help and support with the organisational aspects of the conference.

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Links

1 Workshop programme: https://www.eso.org/sci/meetings/2023/binaries/programme.html
2 Presentation slides on Zenodo: https://zenodo.org/communities/binaries2023?q=&l=list&p=1&s=10&sort=newest
3 `Conference summary: https://zenodo.org/records/10372015

DOI: 10.18727/0722-6691/5360

Fellows at ESO

Jakub Klencki

"What would happen if gravity was suddenly switched off? I mean something really substantial." A classic question to be asked in the middle of the night. A couple of erratic attempts later ("we would all start floating?" or "the Earth would fly away from the Sun?") the puzzle master reveals the answer: "The Earth would explode! As a result of pressure that normally counteracts the forces of gravity." Aaaaahhhh… our jaws dropped. We were awarded some small pity-points for our failed guesses and told to keep going. Further down deep into the forest, under the moonlight, somewhere in central Poland, on a scavenger hunt for... well, 15 years later I don't quite remember what we were after.

That educational exchange took place at a summer camp organised by Astronomy Club Almukantarat. They really knew how to make learning about science and astronomy cool: camping in tents, classes during the day, stargazing at night. Campfire guitar songs and surprise quest missions. A somewhat different style was that of the Polish Child's Fund, a volunteer-driven organisation that would plant us science-hungry teenagers into research labs and institutes for a week or two so that we could see it first hand. Or maybe even run our own experiment, if we were lucky. Nothing short of extremely lucky and fortunate in any case, to have all such opportunities. By the time university came, attempting to do research for life and living felt like the only natural choice. In comparison, the world outside academia seemed like a vast and somewhat terrifying unknown. Before I knew it, I became absorbed into the Borg.

When studying astronomy, one gets introduced to truly fascinating concepts, some of which may seem close to the line between science and fiction. Take 'common envelope' stars as an example. One star flies into another, much larger, giant star, such that it becomes engulfed by the extended envelope of the giant. Moving through the gaseous medium, the star experiences drag, slows down, and spirals in towards the centre of the giant. It plunges through the fluffy envelope like a gloved hand through a cover of fresh snow; the star's movement scatters and disperses the low-density envelope away into space, such that after a while the giant becomes fully unclothed, its inner dense core revealed. We call it unbinding the envelope. Never observed directly in real time owing to its rapid nature, common-envelope inspiral is surely a rather complex process. A fuel for the imagination of any student of physics who would immediately come up with several reasons (often very creative) explaining why they could not derive the outcome of a common-envelope inspiral on a piece of paper. Lo and behold, a professor comes over to *estimate* the outcome with a few lines of concise equations and a plethora of simplifying assumptions. Isn't that beautiful? Astronomy is often not terribly precise. After all, we are observing stars and galaxies millions of light-years away rather than running a well-controled lab experiment. Some of my fellow students did not like it, preferring the more exact and strict regime of mathematics or theoretical physics. But I was all in for back-of-the-envelope simple calculations or numerical simulations. My master's thesis boiled down to estimating how often in our galaxy a star would fly into its companion star (that it was orbiting in a binary) as a result of a dynamical perturbation induced by a third object flying closely by. The result: well, not too often, as it turns out. But astronomy is a safe space for funky ideas.

After a four-year period as a PhD student at Radboud University in the Netherlands, I eventually found my way to ESO. In my current work, I run numerical simulations to model interactions between stars living in close pairs (binaries) as they transfer gas between each other. I focus on massive stars, at least ten times as massive as the Sun. I try to understand how massive star binaries may lead to the formation of merging pairs of black holes or neutron stars. Since 2015 we can detect such mergers because they emit gravitational-waves. About 100 merger events have been observed so far, but with the increasing sensitivity of detectors this sample will soon skyrocket into millions of mergers detected per year (or one every few seconds). Our numerical work on massive star binaries will be needed to interpret this wealth of data and the ESO telescopes such as the VLT and ELT in the near future will be instrumental in calibrating the models. The code I use solves the same hydrostatic equilibrium equation balancing gravity and pressure in Earth that was needed to solve that midnight puzzle at an Almukantarat summer camp. And I still approximate common-envelope evolution with a few simple equations and a set of crude assumptions. For now, the quest continues.

Louise Dyregaard Nielsen

I love telescopes. I love them to such a degree that I have let my life go wherever the observing conditions are good. I love how humankind built these vast, complicated structures with the sole purpose of understanding the Universe we live in. I love that we can learn so much from such limited information delivered by photons (and in the age of multimessenger astronomy, by electrons and gravitational waves).

Growing up in the Danish countryside, the night sky was dark and easily available. As a young child, I was obsessed with stars, and I probably read through every single astronomy book available at my local library. In 1997 the comet Hale-Bopp was incredibly bright in the northern hemisphere and was visible night after night. I remember going out to spot it with my older brothers as it got brighter and brighter in its orbit around the Sun.

Despite my early fascination with the night sky, I did not know if astronomy was a real career and I had no idea what a scientist was or what they would do for work. There were no academics in my surroundings, and generally I doubted the wisdom of pursuing a career based on a childlike fascination. So after high school, I took a gap year to consider options. I worked in elder care and travelled around Central America where I picked up some Spanish. I spent that year talking to people about what they liked about their lives and jobs, and I found myself always circling back to the idea of becoming an astronomer. I started studying physics at the Niels Bohr Institute (NBI) in Copenhagen, where I met a fantastic group of new friends (all of them so smart) while getting introduced to the world of academia and science. I enjoyed physics, but it was not until I had my first astronomy course during my undergrad that I truly felt motivated to learn.

To be honest, I was not a very good university student and I struggled with time management and balancing studying with work and social events. But I scraped by in my bachelor's degree and started a master's in physics and astronomy feeling somewhat burned out. I decided to study half-time, while working as a high school teacher, teaching maths to 16–18 year olds. At the same time, my university classes were almost entirely astronomy-based, which was great! I also took on a part-time job as a research assistant in a lab at NBI that builds cameras for astronomy use. It was this job, combined with a visit to the Nordic Optical Telescope (NOT) in La Palma, that made me realise I probably enjoyed the methods of observational astronomy more than anything else. In the last year of my master's degree, I got a job as a student astronomer at the NOT, and I worked there while finishing my master's thesis.

From La Palma, I moved to Hawai'i for a few months where I worked at Gemini North Observatory before going back to Europe to take up an internship at the European Space Agency (ESA). It was there I began my first project on exoplanets, simulating spectroscopic observations of atmospheres with JWST/NIRSpec. This position became my stepping stone to starting a PhD in Geneva, Switzerland on measuring the masses of transiting planets.

This was a fantastic time to join the field of (transiting) exoplanets. Harvesting the fruit of years of ground-based surveys such as WASP and Kepler/K2 in space, while anticipating new space missions, TESS and subsequently PLATO, that would give us thousands of transiting planets around stars bright enough to follow up with detailed studies. Simultaneously, the field of radial velocity follow-up was reaching new goals as more instruments came online, namely VLT/ESPRESSO, providing unprecedented precision, and more recently NIRPS at the ESO 3.6-metre, operating in the near-infrared. Today, with more than 5000 exoplanets known, we are starting to get an idea of the general populations of exoplanets, though our detection sensitivities do not yet allow us to detect true equivalents to the planets in our Solar System.

Like many others, I finished my PhD in the depths of COVID-19. During this time I moved to Munich where my partner had got a job. We were determined to defeat the two-body problem experienced by many couples in academia. I started a short postdoc in Oxford but worked remotely as the university was fully working from home, before taking up duty at ESO as a fellow.

Working at ESO is very different from a university, but not unlike my experience at ESA. On a day-to-day level, I enjoy talking to colleagues with different backgrounds and expertise, and truly connecting with what it means to run a world-leading observatory. At ESO, I find that there is more of a 'helicopter perspective' on astronomy as a whole, with a focus on how we can be of service to a large, diverse community. As one of the few people at ESO working on exoplanets, I try to voice the needs and future concerns of my sub-field whenever I can. With ESO's Extremely Large Telescope just around the corner, and in particular the high-resolution spectrograph ANDES, the next steps for exoplanet science have already been taken, and we do not seem to be slowing down any time soon.

ESO/G. Vecchia

This drone image, taken in late September 2023, captures an aerial view of ESO's Extremely Large Telescope (ELT) dome at night. It already had the recognisable spherical shape of a telescope enclosure.