The Messenger

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ESO at 60: Looking Forward
ESPRESSO Probes the Fine-structure Constant
CUBES, a New *U*-Band Spectrograph for the VLT

ESO
60 years

ESO, the European Southern Observatory, is the foremost intergovernmental astronomy organisation in Europe. It is supported by 16 Member States: Austria, Belgium, the Czech Republic, Denmark, France, Finland, Germany, Ireland, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland and the United Kingdom, along with the host country of Chile and with Australia as a Strategic Partner. ESO's programme is focussed on the design, construction and operation of powerful ground-based observing facilities. ESO operates three observatories in Chile: at La Silla, at Paranal, site of the Very Large Telescope, and at Llano de Chajnantor. ESO is the European partner in the Atacama Large Millimeter/submillimeter Array (ALMA). Currently ESO is engaged in the construction of the Extremely Large Telescope.

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ESO at 60: Looking Forward

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[1] ESO

After a very successful 60 years of challenges and achievements, ESO is an organisation enabling fascinating astronomical discoveries with a broad portfolio of world-leading telescopes and instruments. The ESO business model has consolidated itself as a remarkable success. In this article I review where ESO stands today, attempting to understand what the keys to its success are, and I set out some views about where the organisation should head in order to capitalise on its strengths.

ESO in context

The European Southern Observatory was born out of the ashes of a Europe broken by the second world war, when a group of visionary astronomers saw that international cooperation was the only basis on which European astronomy could face the future. ESO's early history was masterfully described by Blaauw (1991), the growth of ESO after its initial mission was put in context by Woltjer (2006), and the first 50 years were comprehensively reviewed by Madsen (2012). I will not attempt to write an otherwise superfluous historical review of the first 60 years of ESO here. I have had the honour of witnessing closely the last 16 years of ESO, either as Council delegate, President or Director General (and in between as chair of the ALMA construction lessons learned panel in 2015 and chair of the Observing Programmes Committee in 2016). These years are too recent to be considered history, but they influence considerably the contents of this article.

As declared in the preamble to the Convention (endorsed initially by five Member States in 1962, and over the last 60 years by another 11 so far[a]), ESO's mission was to provide better observational coverage of the southern sky, especially the centre of the Milky Way, by equipping an observatory in the southern hemisphere with 1-metre- and 3-metre-class telescopes, and at the same time facilitating the sharing of information on astronomical topics across the Member States. It may have taken 60 years, but we should not forget that the Nobel-prize-winning studies of the four million solar mass black hole in the centre of the Galaxy[1] as well as the image of its shadow[2] were enabled, among other efforts, by ESO's successful deployment of world-leading optical and millimetre-radio telescopes in Chile. It is equally remarkable that the Convention preamble states that our ability to observe the southern sky was limited 60 years ago, while today many of the most powerful telescopes in operation, construction or planning are sited in the southern hemisphere. ESO has been a major contributor to this shift.

ESO was created and has remained a science-driven organisation. The organisation enables astronomical research by delivering data from world-class facilities to the scientific community, for which state-of-the-art telescopes and instruments are designed, built and operated. As of July 2022[3] a grand total of almost 19 000 refereed papers using data obtained in ESO's observatories (or in ESO's share of time on the telescopes in partnerships like ALMA or APEX) have been recorded. Among those there is an impressive list of breakthroughs in virtually all corners of astronomy, obtained from large and small observing programmes alike, as well as from the ESO science data archive (Sterzik et al., 2015). In addition to the above mentioned breakthroughs on the Sgr A* supermassive black hole, astronomers using ESO's telescopes discovered the accelerated expansion of the Universe, obtained the first direct image of an exoplanet, found planets orbiting Proxima Centauri — the star nearest to the Sun, identified the first long gravitational wave event as a kilonova, provided evidence that protoplanetary discs around young stars are the cradles of planets and found a Milky Way-like galaxy at redshift 4.2. This is a massively biased and unfairly minuscule selection of scientific achievements, which is quoted here merely to illustrate the calibre of some of these discoveries.

ESO today

What ESO does can be mapped onto its two mission drivers (to build and operate world-class astronomical facilities and foster international cooperation for astronomy), plus a third area comprising all the activities necessary to support its mission. ESO's activities are often organised in Programmes, which are comprehensive sets of projects and operational work, in some cases needing explicit approval by Council.

La Silla Paranal Observatory

The La Silla Paranal Observatory is a comprehensive Programme that includes the operation of an observatory at its various sites, complemented by a standing development Programme. It includes three observatory sites in Chile — La Silla, Paranal and Chajnantor — along with the operations backend in Garching and the Paranal Instrumentation Programme.

At La Silla, ESO's first observatory site and in operation since 1969, there are two facility telescopes running: the 3.6-metre telescope and the 3.5-metre New Technology Telescope (NTT). Their instrumentation, and therefore the science they deliver, focuses on radial velocities and transient follow-up respectively. NIRPs (a radial-velocity near-infrared spectrometer) and SoXS (a very broad spectral band low-resolution spectrograph) will equip the 3.6 metre and the NTT respectively for the next five years. In addition, La Silla is home to several hosted telescope projects, built and operated (remotely) by institutes in ESO Member States and to which ESO provides technical support as requested. These three elements set the five-year horizon of La Silla, whose future after that period will have to be carefully considered in the overall ESO and worldwide context.

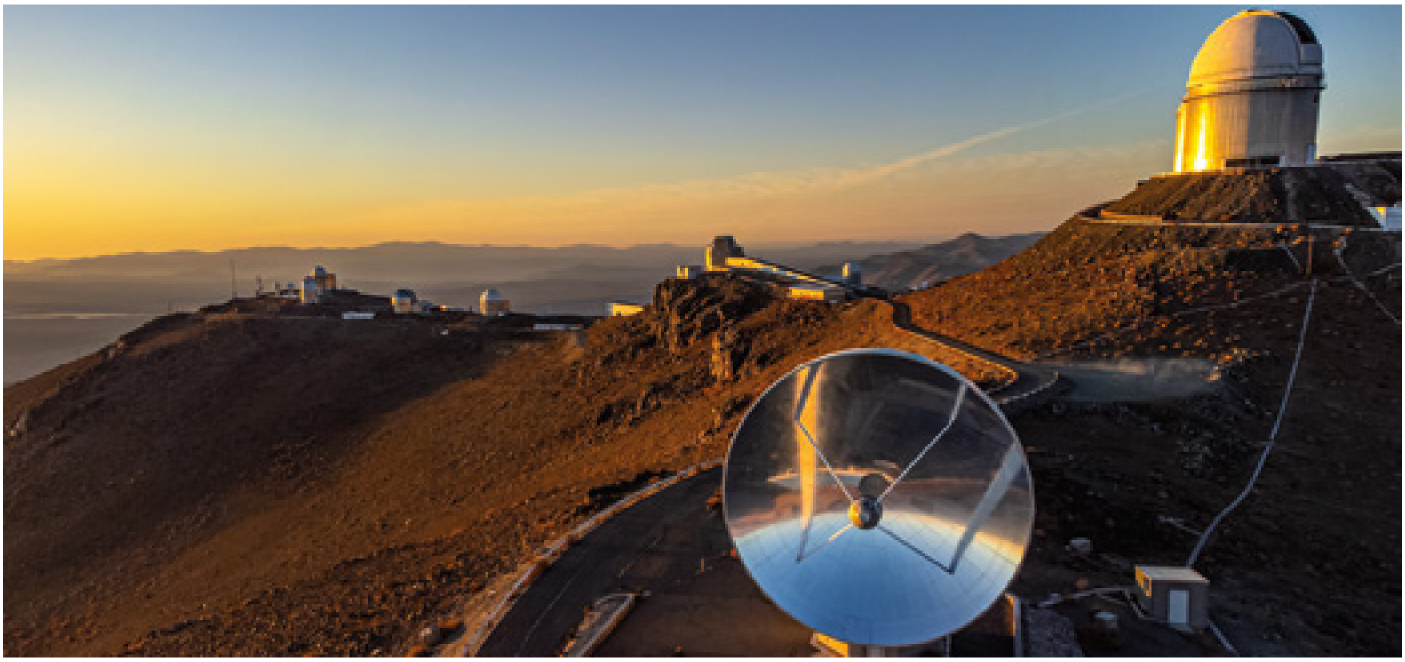
Paranal is home to the most powerful optical telescope system in the world. The VLT (Very Large Telescope) with its four Unit Telescopes (UTs, each with an 8.2-metre primary mirror) and the four movable Auxiliary Telescopes (ATs, each with a 1.8-metre primary mirror), along with the whole VLT Interferometer (VLTI) infrastructure, together offer a very ample coverage of parameter space at optical and near/mid-infrared wavelengths. Each UT is equipped with three facility instruments, currently comprising CRIRES, HAWK-I, KMOS, FLAMES, FORS2, MUSE, SPHERE, UVES and X-shooter, with ERIS in commissioning[4]. The VLTI offers three facility instruments (PIONIER, GRAVITY and MATISSE) and the incoherent combined UT coudé focus hosts the ESPRESSO spectrograph. UT4 is a fully adaptive-optics telescope equipped with a Laser Guide Star facility, and as part of the development of the GRAVITY+ project, UT1, UT2 and UT3 are also being equipped with laser systems. The 4.1-metre survey telescope, VISTA, is being transformed to host the 4MOST multi-object spectrograph. After 11 years of being part of the Paranal system, the VST (VLT Survey Telescope) is becoming a hosted telescope project for INAF as of October 2022.

APEX has been operated at Chajnantor by ESO on behalf of a partnership with the Max Planck Institute for Radio Astronomy (MPIfR) in Bonn and the Onsala Space Observatory since 2005. From 2023 to 2025 it will become a hosted telescope project for MPIfR, and after that period ESO will step out of APEX, leaving behind 20 years of success.

Similarly to what happens in space science missions, where a Mission Operations Centre is supported by a Science Operations Centre, the on-site facilities of the La Silla Paranal observatory are complemented by a support structure at ESO's headquarters. This includes the Observing Programmes Office, responsible for administering the observing time at these telescopes, the User Support Department and a Back-End Operations department which develops and operates the science archive, pipelines, etc.

The future of the Paranal observatory site is being shaped now, triggered by the requirement to operate ESO's Extremely Large Telescope (ELT)[5] as part of the Paranal system. The scalability of the current operational concept for the VLT and the VLTI to the ELT is highly questionable, given its size and complexity. Here "operations" do not (only) refer to science operations, but rather to technical operations, maintenance etc. A Paranal Integrated Operations Programme (IOP), currently in Phase A, is being set up to define an operations concept which is lean, remote and yet high-performance. By moving the centre of gravity of operations to Santiago or Garching, the number of staff that actually have to travel and live at the observatory will be optimised.

A development programme named the Paranal Instrumentation Programme (PIP) ensures the competitiveness of the instrumentation in the observatory. Upgrades of existing instruments or new instrument developments are performed in partnership with consortia of R&D institutes in the Member States, maintaining the comprehensive instrument suite that equips the VLT and VLTI, ensuring this facility remains world-leading. While the VLT and VLTI had first- and second-generation instrument "waves", the PIP has become more of a sustained effort which interleaves substantial upgrades of existing instruments with the development of fresh ones.



Zdeněk Bardon/ESO

The sunset creates a magnificent setting over the telescope village of ESO's La Silla Observatory in the Chilean Atacama desert. La Silla is home to many telescopes, some still in active use, like the ESO 3.6-metre telescope situated at the highest summit to the right and currently on the hunt for exoplanets.

ALMA

ALMA[6] (the Atacama Large Millimeter/submillimeter Array) is the most powerful radio telescope in the world at sub/millimetre wavelengths. It was built and is being operated by a partnership consisting of ESO (37.5%), the US National Science Foundation (NSF; 37.5%) and Japan's National Institute of Natural Sciences (NINS; 25%). At the observatory site, at over 5000 metres on the Chajnantor Plateau, there are 66 antennas (54 of 12 metres diameter and 12 of 7 metres diameter) which can be relocated into different configurations (thereby delivering different resolutions), the clocking and local oscillator, as well as the correlator. The Operations Support Facility is at 3000 metres near San Pedro de Atacama. ALMA began science operations in late 2011 and is possibly the most oversubscribed ground-based telescope. This is especially true for the community in the ESO region, which leads the number of proposals submitted as well as the number of papers published across the partnership.

ALMA is managed on-site by a Joint ALMA Office (JAO), established and staffed by the three executives (ESO, NAOJ and NRAO) under the authority of the ALMA Director, who also leads the entire observatory across the partnership. Off-site operations support is provided by the three executives in Garching, Mitaka and Charlottesville. Science operations are conducted jointly by the JAO and the support centres in the three regions, with support to users provided through the three ARCs (ALMA Regional Centres). In the case of the ESO region, the ARC is distributed, with contributions from a variety of nodes who help with the science operations in specific areas of their expertise and provide support to their user communities.

Synergistic actions are being undertaken to facilitate the joint scientific exploitation of the La Silla Paranal and ALMA observatories by the ESO community. The ESO Science Archive Facility provides interfaces to data from both observatories. Starting in ALMA observing Cycle 10, dual time allocation will be possible together with the JWST, VLT/I and JVLA.

From the start it was foreseen that ALMA would need a development budget to maintain its scientific competitiveness. An ALMA Development Roadmap was adopted in 2018[7]. The most challenging ALMA Development project is the Wideband Sensitivity Upgrade (WSU) which will require a significant upgrade of the ALMA correlator (which may be sited at 3000 metres), new software and archive facilities, infrastructure work and the upgrade of some of the receiver bands.

ESO's Extremely Large Telescope

Following approval by Council in 2014, construction of the largest telescope in the world is progressing at very good pace. ESO's Extremely Large Telescope (ELT)[5] is being erected on the top of Cerro Armazones, only about 20 kilometres (and about 40 minutes' drive) away from Paranal. The ELT has an innovative six-mirror design (five mirrors as part of the telescope itself and one as part of the pre-focal stations); the primary mirror (M1) is 39.3 metres in diameter and is made of 798 hexagonal segments. The secondary mirror (M2, whose size was a technical driver limiting the total aperture) will have a diameter of 4.2 metres and will be placed 60 metres above M1. M3 is a concave 3.2-metre mirror, the 2.4-metre deformable "adaptive optics" mirror M4 will use over 5300 actuators, and M5 will tip-tilt to remove the sky background in real time at up to 4 Hz (M4 will correct at frequencies from 4 to 20 MHz).

Instruments will be placed on two gigantic Nasmyth platforms (an entire VLT UT would fit on one of these platforms). The first suite of ELT instruments is under development by large consortia of institutes together with ESO. ELT instruments are particularly challenging because of their size and complexity, and also the fact that they are being developed for a telescope which is still being built. These instruments are meant to be facility instruments and not experiments, and that calls for a very close collaboration between the instrument consortia and ESO. Ways to achieve a better integration between the ESO team developing the telescope and the instrument consortia are being pursued. The first-generation instruments are:

- MICADO (in all likelihood the first-light science instrument), a near-infrared, high-resolution camera and spectrograph;
- HARMONI, a workhorse integral-field unit covering the spectral range from 470 nm in the optical to 2450 nm in the infrared;
- MORFEO, a multi-conjugate adaptive optics module feeding MICADO (plus a second host instrument); and
- METIS, a mid-infrared instrument which combines imaging, spectroscopy and polarimetry capabilities.

The first elements of the next-generation ELT instruments will be ANDES, a high-resolution ultra-stable spectrograph and MOSAIC, a multi-object spectrograph. Further down the line, an extreme adaptive optics instrument (provisionally called the Planetary Camera Spectrograph) is foreseen, its ultimate goal being to image Earth-like planets around nearby solar-type stars. There are technologies that need to be matured before such an instrument can be developed, and ESO is helping their development.

The ELT construction programme includes the civil work and infrastructure at the mountain, the telescope and the first-generation instruments. Virtually all the construction contracts have been placed, most of them already in manufacturing phase. Civil work for the Dome and Main Structure in Cerro Armazones is expected to be finalised during 2023, while the Dome is being assembled and the telescope Main Structure is being erected. In Paranal, the ELT Technical Facility (ETF) hosts, among other equipment, two coating plants for the mirrors, ready to start coating the first batches of polished M1 segments that will arrive in 2023.

The optomechanics is progressing well, and more than half of the glass for the M1 segments has been cast. Polishing of all mirrors is ongoing in different phases, along with the integration of segment supports, position actuators, edge sensors etc.

Optical control plays a key role in making sure that the telescope will function as such once it is integrated and can therefore be commissioned. This is a work package where the best of the skills of the ESO engineers and scientists is put at work. A critical element is the Phasing Diagnostic Station (PDS) which is being internally developed. Control systems make up another work package with a lot of ESO internal work by ESO's engineers, totalling a very large effort.

The enthusiasm of ESO people, instrument consortia and industry are the best guarantee of success for this joint venture, which is in both absolute and relative terms the largest project ever addressed by the organisation. The current schedule foresees the start of ELT Science Verification (and therefore ELT first science light) in late 2027, although the impact of recently materialised risks still needs to be fully considered. This puts ESO's ELT first among the class of all extremely large telescopes to go on sky.

Cherenkov Telescope Array

ESO has signed agreements to host and operate the southern part of the Cherenkov Telescope Array (CTA)[8] in the Paranal-Armazones territory, in a way that is cost neutral for ESO. CTA will be the first observatory to observe the sky in very high energy (VHE) gamma-rays, spanning approximately 0.1 to 10 TeV. Gamma-ray photons at these energies are detected through the short Cherenkov radiation flashes that they generate when interacting with Earth's atmosphere and producing cascades of subatomic particles. Arrays of purpose-made optical telescopes equipped with ultra-fast cameras sensitive to blue/UV light detect these flashes and locate the direction of the incoming gamma-ray photon as well as its energy. CTA will have large, medium and small Cherenkov telescopes which provide sensitivity at low, medium and high energies in the VHE gamma-ray domain respectively.

CTA will be built by a European Research Infrastructure Consortium (CTA-ERIC), a legal figure under European Union legislation and of which ESO is an 8% founding partner. A telescope configuration dubbed *Alpha* has been considered affordable by the future CTA-ERIC members, and it is being optimised (within programmatic constraints) to deliver the best science. CTA-North (sited at the Observatorio del Roque de los Muchachos on the Canary island of La Palma, Spain) will host large and medium telescopes. The CTA-South site in ESO's Paranal-Armazones area has medium and small telescopes, although there is a recent development that may add two or three large telescopes.

ESO/B. Tafreshi (twanight.org)

The Milky Way glitters above the ALMA array in this image taken from a time lapse sequence during the ESO Ultra HD Expedition.

While the establishment of the CTA-ERIC is being completed and a construction proposal can be considered and eventually approved by the new entity, preparatory work is being done. The access road to the CTA-S site is complete, while the design of the foundations of the telescopes and the connection to the Paranal-Armazones power grid are in ongoing.

ESO will offer to scientists in its Member States 10% of the CTA observing time, both in the north and in the south. This will bring scientific opportunities to maximise the synergies between CTA and the rest of ESO's telescopes.

Fostering international cooperation for astronomy

The second element of ESO's mission manifests itself in a variety of actions that the organisation maintains. Some of them are related to science — for example organising conferences and workshops around scientific topics, training early career scientists through astronomy studentships at ESO (where PhD students spend time at ESO while doing their research work), the prestigious ESO Fellowships, through which many brilliant astronomers grow professionally and eventually go back to institutions in the community fostering engagement and cooperation with ESO and among Member States. Studentship and fellowship programmes are also successfully taking shape in engineering. Programmes for short-term visits of senior and junior researchers, internships in several disciplines (astronomy, engineering, education, communication, science policy etc) and summer scholarships are other vital elements of the way ESO fosters cooperation.

The organisation conducts a comprehensive set of communication and outreach activities and generates many high-quality publicly accessible materials. The targets for these activities encompass the scientific community, science policy decision makers and society at large, especially in the ESO Member States and Chile. Thanks to these efforts, ESO's activities and their societal impacts are better understood, resulting in support for the organisation. The ESO Supernova Planetarium & Visitor Centre in Garching provides the primary capability for education and outreach, with its focus on families, schoolchildren and school teachers. Site and virtual guided tours to the ESO observatories in Chile complement this effort.

ESO further contributes to international cooperation by working together with other observatories, agencies and governments on sky protection from light contamination originating both from the ground and from satellite constellations.

Internal support actions

Together with all the necessary administrative tasks (for example, facility & logistics management, finance, contracts & procurement, human resources, legal & institutional support, information technologies), astronomical research is conducted by all ESO astronomers (staff, fellows and students) alongside their functional duties. Likewise, engineers engage in R&D projects, which in some cases develop into elements of a forward-looking Technology Development programme. More recently an organisation-wide Quality & Information Systems programme has started with the goal of increasing the organisational efficiency by streamlining and easing processes.

Best practices

ESO adopts standards that are broadly shared and that are part of ESO's Values. In this way ESO may be seen by some as a role model. Specific elements include:

- those related to sustainability in the social, financial and environmental sense, including those aspects related to Diversity, Equity and Inclusion;
- a Respectful Workplace policy which does not allow for any type of harassment and provides tools to deal with unrespectful behaviours;
- a set of family-friendly policies leading to a general work-life balance, where extraordinary efforts remain exceptional and not the baseline;
- rather strict Safety policies;
- a rethinking of the criteria being used in academia for hiring and assessing performance in the research environment; and
- implementation of codes of conduct applicable to meetings and workshops.

Keys to sustained success

Looking back at the 60 years of ESO's challenges and successes, but also looking around at other scientific organisations of similar scope (not only in astronomy), I attempt to summarise below a distinctive set of features that in my opinion has allowed this organisation to grow and succeed for decades.

Engagement with the astronomical community at large

The process by which ESO decides on a new observatory, which telescope to build, or which instrument to develop next has a strong involvement by the community that the organisation serves, where science plays a driving role. Council approval is required to start a new observatory or Programme (for example the VLT, APEX, ALMA, ELT and CTA Programmes). Prior to starting a large new Programme there is a lot of preparatory work by ESO and the community, in which the Scientific and Technical committee (STC) plays a pivotal role. The STC, which is appointed by the Council, is constituted by experts sampling all Member States (but not representing the views of their specific constituency). The importance of the STC cannot be overstated as it acts as an adviser to the organisation by recommending scientific and technical priorities based on science drivers from ESO's global community.

ESO maintains a task force of active astronomers with excellent research credentials, who also perform necessary functional duties. These scientists need to remain scientifically active in order to enable a fruitful engagement between ESO and the community it serves.

It is also strategically important that ESO serves the broadest possible community, as reflected in the science operations policy[9]. Approved observing proposals range from a few hours of telescope time to hundreds of nights, depending on the scientific goals. While the scientific productivity of large programmes (per unit observing time) is on average higher than for shorter normal programmes (Sterzik et al., 2015), there are outstanding science results coming from all types of observing programmes. A balance between large and smaller programmes is kept by limiting the total amount of observing time granted to large programmes to 30% with the VLT and VLTI, although that limit is never reached.

Capacity to successfully manage the construction of large telescopes/observatories and operate them

While several institutions in ESO Member States have a tradition and well-developed skills in the design, building and even operation of instrumentation, the capacity to design, build and operate facility-type astronomical infrastructures is a different challenge. This requires a project management culture, strong systems engineering knowhow and practice, strong administrative support (for example in contracts and procurement), a set of very specific engineering skillsets and disciplines, and all this melded together with a critical scientific oversight during the development of a facility project. The infrastructure needs to be developed, maintained, and operated in the generally remote places where the telescopes end up being placed.

The requirements to build and operate a facility-type telescope or observatory are not the same as for an experiment, where the participating teams would not only design, build and operate, but also be the users of the telescope. This is understood today, for example, by the CTA Observatory, as this will be the first ever VHE gamma-ray *observatory* on the ground, following on from the successful experience from experiments like HESS, MAGIC or VERITAS.

ESO not only possesses the skills to design, build and operate large astronomical facility-type telescopes and infrastructures, it treasures a multiplicity and diverse set of experiences, having done it several times in its history. In times where new research infrastructures often require the creation of a new organisation (an Intergovernmental Organisation, an ERIC or other legal forms), ESO's standing capacity of undertaking such big challenges is a major asset of the organisation at the service of its community.

Partnership with R&D institutes in instrument development

The current model whereby the instruments for the optical/infrared telescopes are developed in partnership with consortia of R&D institutions from the Member States has proven strong and successful for decades. There are many reasons for that, not least that scientifically engaged teams have all the motivation to deliver the best instruments for the benefit of all. The scheme brings additional funding and recognition from the national agencies to their instrument teams, enables science objectives requiring large amounts of observing time being tackled by the team who knows best the instrument (making use of the Guaranteed Time Observing granted by ESO in compensation for their contributed effort) and samples the best combination of skillsets across ESO and its Member States. ESO contributes to instrument development in cash, in critical components and in GTO.

The governance of the relationship between ESO and the consortia has evolved over time and is kept under constant scrutiny. While there is a formal contractual agreement between ESO and the lead institution in the consortium, approved by Finance Committee for the cash contributions and by Council for the GTO, the relationship is meant to be both formal and cooperative. ESO acts in the role of oversight and customer, but also as contributor to the instruments. Adjustments to the practice of the necessary reviews in various phases are being considered, bearing in mind that the ultimate joint goal is to build, install, commission, operate and maintain instruments that will enable world-class science. This model has worked very successfully at the La Silla Paranal observatory and is now making solid progress for the ELT instrumentation programme.

The ALMA Development programme, conducted across the partnership, has so far been executed in Europe largely through outsourcing of the work to research institutes and companies. This means that ESO pays in cash and oversees the development. In line with the scheme for the optical/infrared telescopes, Council has recently approved a policy where additional contributions to projects of the ALMA Development programme can be rewarded with GTO, provided there is a supporting scientific motivation. This policy is still to be set in motion, but it opens a way to engaging the R&D institutions in the ESO Member States with the ALMA Development programme in a more collaborative way.

Multi-programme, multi-wavelength facilities

The ESO Convention established in 1962 and ratified by all its current 16 Member States sets up the initial programme of the organisation which included, among other smaller elements, *"...A telescope with an aperture of about 3 metres"*. This ambition was indeed realised when the 3.6-metre telescope in La Silla started operating in 1977. One of the biggest strengths of ESO during the last 60 years is that Member States have *unanimously* agreed at various points in time on the development of the unique battery of telescopes of various sizes, technologies and wavelengths that constitute its current portfolio.

ESO started as an observatory and has evolved into an organisation that builds world-leading telescopes and advanced instruments, while operating others which remain at the forefront of worldwide astronomy, in particular thanks to upgrades of their infrastructure and instrumentation.

In the late 2020s ESO will offer to its research community a set of facilities covering the submillimetre and millimetre regime (ALMA), the mid/near-infrared and optical wavelengths (VLT/I and ELT) and the TeV gamma-ray regime (CTA). Operational and scientific synergies across these facilities are an asset of the organisation and provide added value to the scientific community.

Through agreements with ESA and soon with SKAO, a fuller multi-wavelength (and eventually multi-messenger) coverage can be offered to the scientific community, creating further opportunities.

Legal status and business model

The status of ESO as an Intergovernmental Organisation (IGO) comes with requirements and necessary effort, but the balance over other models is positive overall. Like CERN, ESA and the rest of the IGOs, ESO has its own legal architecture and support system, which require attention and funding from the Member States.

These overheads are largely compensated by the commitment from the Member States under the obligations that come with being part of a treaty organisation. Since the ESO Convention has been ratified by the Parliaments of all its Member States, the support from the national governments is extremely solid. This has allowed long-term planning during the last 60 years, essential to committing to large projects that take one or two decades to develop and remain operational for two or three more decades.

The financial contributions to ESO from each Member State are defined in the Financial Protocol attached to the Convention and are in proportion to their net national income. Other than in the original programme set in the Convention, every Member State can choose whether to participate in any other programme. However, as mentioned before, a major strength of the organisation has been that *all new programmes* have been subscribed by *all Member States*, and they all contribute financially as per their net national income.

The immediate returns of ESO membership for each of Member States (observing time, participation in instrumentation development projects, industrial contracts, staff at ESO among others) are all achieved through competitive processes. The fact that there is no georeturn is an incentive for individual Member States to better support their scientific community, instrument developers, and education, as well as offering opportunities for industrial development. ESO has the tools and puts in the effort to help improve these returns when they are not good enough, in collaboration with the Member States. But all in all, the ESO business model promotes development of all areas related to astronomy in the Member States.

Governance

ESO has built a very constructive, functional and robust model for its governance. The ESO Council, the organisation's governing body, plays a critical role in this. It is assisted by two standing auxiliary bodies, the Finance Committee and the STC, who support and make recommendations in their respective areas. This is all rather standard in the governance of

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

This image depicts the four powerful laser beams leaving Unit Telescope 4, or 'Yepun', at ESO's Very Large Telescope (VLT) in Chile's Atacama desert. These form the VLT's 4 Laser Guide Star Facility, which enables astronomers to take extremely crisp images of the cosmos by employing a technology known as adaptive optics.

many scientific international organisations, be those IGOs or of any other legal format.

The most remarkable feature of the way the ESO Council works is that no matter how many difficulties are encountered, the attitude of Council is always to care for the greater good of the organisation and its activities. The legitimate national interests and aspirations of individual Member States are always a secondary priority. After 60 years of continued success (admittedly with difficult periods and ups and downs), I would dare to say that ESO's governance model is inspiring.

There are specific features and practices that help this to happen. In my view the fact that each Member State is represented in Council by a government representative and by a science representative gives this body a lot of vision. Council discusses finance budgets as well as the spectral resolution of a new instrument. It is not the case that two sets of disjoint dialogues in Council happen; all delegates participate in all debates. Both governmental and scientific delegates get the full picture and exercise well-informed decision-making power over the whole organisation's programme.

A very helpful practice established long ago are the Committee of Council meetings. Council meets formally twice per year in June and December, but in addition the Committee of Council (with the same delegates) also meets twice in between to "discuss". There are no minutes of these meetings (only summaries) as no decisions are made. However, Committee of Council meetings are very helpful to prepare for decisions to be submitted for Council approval, to discuss in-depth strategic topics, to give guidance to the executive and indirectly to strengthen the sense of working together among the delegations.

When looking at other organisations, ESO has a long lead-time for decision making as it aims at having all its Member States converging. Statistically, at any point in time there is at least one Member State, and often several, going through an election process and therefore facing difficulties with approving long-term commitments. However, once the commitment in Council has been achieved, ESO is on the path to deliver.

The most recent example is ESO's ELT[10]. It took time in the early 2000s to achieve consensus among the community in Europe around a single project, and this was achieved in 2006 at a workshop triggered by ESO in Marseille. The start of Phase B of the ELT was approved by Council in December 2006 based on a novel reference design developed in house and with an initial diameter for the primary mirror of 42 metres. After the Phase B and a Delta Phase B to address technical and cost risks, the construction proposal for a 39.3-metre telescope was ready in 2011. It was only in 2012 that 10 of the (then) 14 Member States could approve starting the new Programme, still with very limited funding commitment. Authorisation for the first construction phase of the ELT had to wait until December 2014, with all 14 Member States in support together with the necessary financial commitments. A similar consensus was achieved in December 2020 when Council committed additional funds to provide an appropriate level of contingency, to cover missing scope inside the construction project as well as fund-related activities that ESO had to perform to be able to bring the ELT into operation (in particular the Paranal IOP).

Despite the slow start, the ELT is the most powerful of the class of all extremely large telescopes, the only one that is fully funded and the one which is most advanced in its construction status. Spectacular progress has been achieved since the start of construction in 2015, despite facing technical difficulties inherent to a project of this complexity, social unrest in Chile starting in late-2019, a global pandemic starting in 2020 and a war in Europe starting in 2022. These adverse effects had impacts on the schedule of the project but it continues, nevertheless, to make steady progress.

Going global through partnerships

In 60 years ESO has remained predominantly European with all its Member States today being in Europe. At the same time the organisation has been partnering with Chile since 1963 as a host state of ESO's current telescope portfolio. After 59 years of working together, the status of Chile cannot be simply described as that of a "host state". Chile has developed during that time a very strong and internationally recognised astronomical research community. While observing time granted to the Chilean community has helped this development, by ESO's being an active research actor in Chile and offering opportunities like studentships, fellowships and science visitorships, solid scientific collaborations have been established over the decades.

Chile is today a country with an enormous potential not only in astronomical research, but also in many modern development disciplines like data science, digitisation, and industry 4.0-related disciplines. ESO and the Chilean ANID (Agencia Nacional de Investigación y Desarrollo) have signed a cooperation agreement to co-fund projects needed for the operation of the ELT as part of the Paranal observatory. Training personnel for such activities is a benefit for both ESO and Chile.

There is a lot more that ESO and Chile could do together, and in my view the horizon is that Chile becomes a full Member State of ESO. This would enable the full involvement of Chile (not only the scientific community but all relevant actors) in the present and future of ESO, working side by side with the rest of the Member States, from the standpoint of hosting the current suite of ESO's telescopes. The mutual benefits of the cooperation between ESO and Chile so far have been collected in an ESO report[11], but the prospects for such benefits in a future in which Chile becomes a full ESO Member State would be much broader.

In 2017 ESO signed a 10-year strategic partnership with Australia on the La Silla Paranal programme (both for operations and development)[12]. This has enhanced the existing engagement between the astronomical communities in Europe and Australia, and the VLT/I has become part of the toolbox of Australian astronomy. A very interesting development is that Australia now leads a consortium developing a new multi-conjugate adaptive optics instrument for the VLT called MAVIS[13]. Opportunities are being explored to strengthen the engagement, with the ultimate goal that Australia becomes a full ESO Member State in the coming years.

Beyond that, ESO has not been proactively pursuing expanding its membership in recent years and, with the two exceptions above, contacts have been limited to countries in the European area. Prior to that, the accession agreement that Brazil signed with ESO in 2010 regrettably never entered into force.

ESO adopted long ago the realistic position of not attempting to become a global organisation. There are very powerful astronomy poles in other parts of the world and ESO has remained largely European. However, ESO has gone global through ALMA with its international partners (NSF and NINS). ALMA really is a world-class and world-wide observatory, involving 20 countries in Europe, North America and East Asia, in collaboration with Chile. It would have been difficult for any of the three ALMA parties to achieve it alone, not only because of the financial envelope, but also because a joint venture of this size and technical complexity has benefited from the competencies and experience in the three regions.

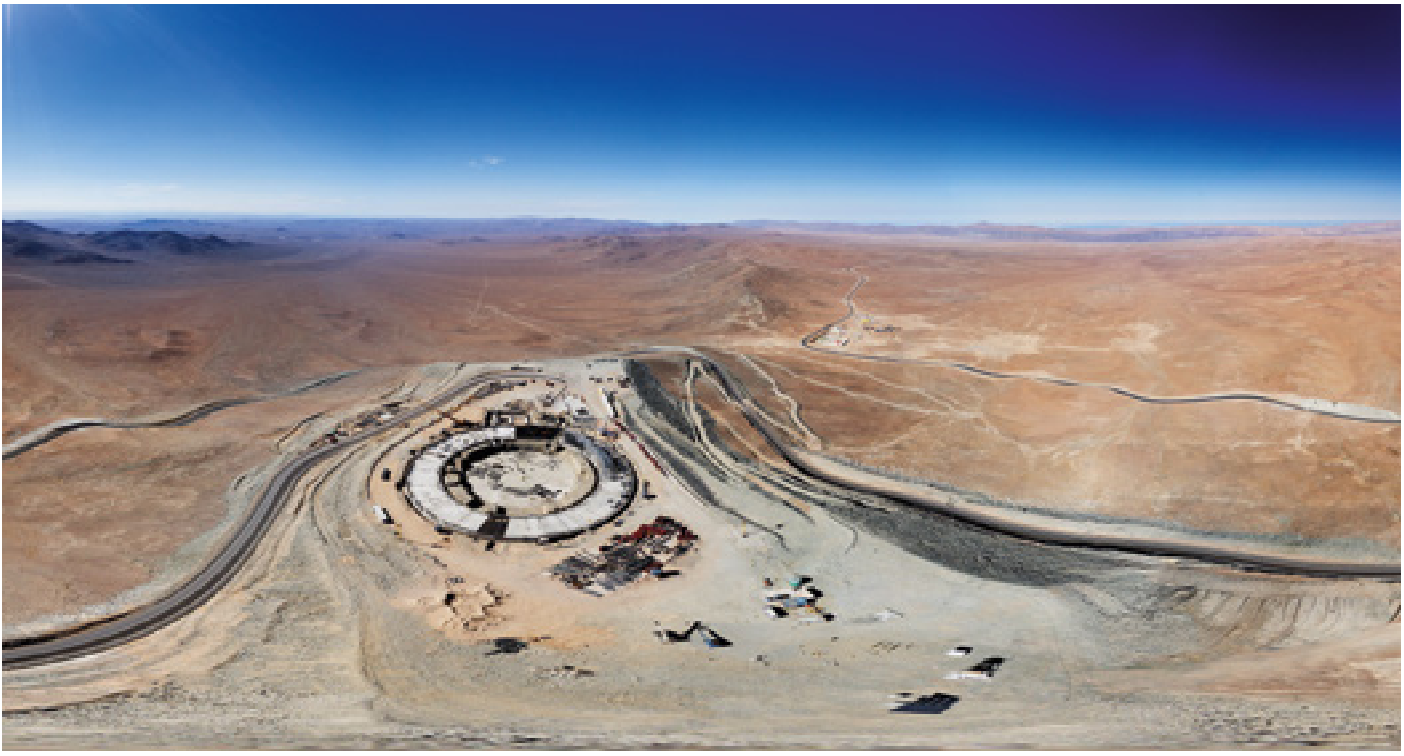
After 10 years in operation, ALMA delivers amazing millimetre and submillimetre observations. The Programme's governance is not particularly simple, but thanks to the engagement of the three ALMA parties and their corresponding executives (ESO, NAOJ and NARO) it works. In fact one could think of a model built on what has been learnt from this scheme for developing future global large ground-based facilities (in astronomy or other fields of science).

The future

During the last few years the ESO Council has taken steps to update the organisation's strategic package, i.e., the formulation of its Mission-Vision-Strategy-Values[14]. This is needed to set the scene for looking at the mid- and long-term future of the organisation.

While the ESO Mission (*why we exist*) was formulated in the Convention, the ESO Vision (*where are we heading*) is currently being updated. At this point the organisation is on track to achieving what was formulated in 2004 as ESO Scientific Strategic Planning (Bender 2005): Build and bring into operation the ELT, while maintaining the VLT/I and ALMA at the forefront of world-wide astronomy.

The current version of the ESO Values (*what are our beliefs*) was approved by Council in October 2021 based on a proposal that combined internal and external views. It is worth recalling them here, as they constitute the pillars on which ESO designs its future: *ESO strives for* ***excellence*** *through* ***innovation****, provides*



G. Hüdepohl (atacamaphoto.com)/ESO

ESO's Extremely Large Telescope is currently under construction at the top of Cerro Armazones in the Chilean Atacama Desert. It is expected to begin scientific operations later this decade and is set to become one of the world's leading astronomical facilities.

outstanding ***services to its communities****, fosters* ***diversity & inclusion*** *and believes in the key role of* ***sustainability*** *for its future. These values of the organisation are realised and maintained by the people working at ESO. The efforts to achieve ESO's values are only possible on the basis of personal values and attitudes:* ***respect****,* ***integrity****,* ***accountability****,* ***commitment****,* ***collaboration****, and* ***clear & open communication****.*

The strategy for the 2020s was approved by Council in December 2020, following a proposal by the Strategy Working Group (Waelkens, Benz, & Barcons, 2021). It focuses on the following drivers:

- Implement and operate ESO's ELT as the world-leading extremely large telescope.
- Ensure that the current facilities remain at the forefront of astronomical investigations.
- Ensure that the organisation is prepared for future projects when financial projections permit.
- Retain ESO's leadership role in astronomy.

Within this strategic framework, the new ESO Vision will guide the organisation once the ELT is on a solid track towards delivering world-class science. I strongly advocate that in formulating this long-term guidance, the *Keys to sustained success* presented earlier must play a decisive role.

A few additional personal considerations on shaping the future of ESO.

- All ESO Values must be considered. As an example, it would not work to focus only on specific aspects of environmental sustainability and forget about diversity or social sustainability. Or to trade off financial sustainability against excellence.
- The societal benefits of ESO's activities[15] should not be overlooked. ESO is publicly funded via the national budgets of its Member States, and therefore must report back to society about its activities and their impact.
- ESO must involve the community when deciding a potential new project, STC being a key interface. In the end the ESO Council will make the decision based on a variety of considerations, but the scientific drivers should play a major role.
- ESO's resilience is a major asset and should be guaranteed. The size and complexity of ESO's next big project should match the available financial and human resources of the organisation. A project of the size and complexity of the ELT (its cost to complete is approximately eight ESO yearly budgets) has probed the limits of what ESO could contribute to a next large project.
- ESO should remain focused on "world-class" telescopes and facilities, noting that this is an evolving concept. In that context, it is unavoidable that ESO will need to consider the future of La Silla in the coming years, even more so when discussing new projects.
- ESO should modernise the way it operates as an organisation and very specifically the way its observatories are operated (cf. the Paranal IOP).

The future of ESO looks very exciting and very bright, as well as challenging. Looking back, one can see a very clear trend. ESO was created at an epoch when the US was clearly running ahead of Europe in terms of large telescopes, to the point that extragalactic observational astronomy was barely achievable in Europe. The 3.6-metre telescope in La Silla was the critical element to avoid falling behind any further. Then in the era of the 8–10-metre telescopes, ESO missed the low hanging fruit for the VLT ahead of the Keck telescopes, although not by a large margin. Instead, the VLT focused on offering a diversity of instruments and this has indeed paid back. I would argue that with the VLTI (already more than 20 years after first fringes!) ESO took the driving seat in NIR interferometric facilities. With ALMA the main actors of world-wide ground-based astronomy, including ESO, came together. ESO now is poised to offer access to its ELT to its scientific community, ahead of other projects like the GMT and the TMT, whose success ESO looks forward to.

That sets the scene for the coming times: ESO's ambition is to develop and operate a diverse portfolio of world-leading facilities with and for its astronomical community, enabling breakthrough scientific discoveries.

Acknowledgements

Many colleagues from the community, from ESO's governing bodies and inside ESO have contributed (sometimes unknowingly) to the thoughts presented here. I want to thank them all for their inspiring wisdom.

References

Bender, R. 2005, The Messenger, 119, 2
Blaauw, A. 1991, *ESO's Early History*, (ESO)
Madsen, C. 2012, *The Jewel on the Mountaintop*, (Weinheim: Wiley-VCH)
Sterzik, M. et al. 2015, The Messenger, 162, 2
Waelkens, C., Benz, W. & Barcons, X. 2021, The Messenger, 183, 3
Woltjer, L. 2006, Europe's quest for the Universe, EDP Sciences

Links

[1] 2020 Nobel Prize in physics: https://www.eso.org/public/news/eso2017/

[2] The Milky Way's black hole: https://www.eso.org/public/news/eso2208-eht-mw/

[3] ESO publication statistics: https://www.eso.org/sci/php/libraries/pubstats/?wcmmode=disabled

[4] Available instruments are listed in the Call for Proposals: https://www.eso.org/sci/observing/phase1.html

[5] ESO's ELT website: https://elt.eso.org

[6] ALMA website: https://www.almaobservatory.org/en/home/

[7] ALMA Development Roadmap: https://www.almaobservatory.org/en/publications/the-alma-development-roadmap/

[8] CTA website: https://www.cta-observatory.org

[9] ESO Science Operations Policies: https://www.eso.org/public/about-eso/committees/cou/cou-154th/external/Cou_1847_rev_Science_Policies_050520.pdf

[10] The road to the ELT: https://elt.eso.org/about/road/

[11] ESO–Chile cooperation: https://www.eso.org/public/products/brochures/brochure_0078/

[12] ESO–Australia partnership: https://www.eso.org/public/news/eso1721/

[13] MAVIS: https://www.eso.org/sci/facilities/develop/instruments/MAVIS.html

[14] ESO's Vision, Mission, Values and Strategy: https://www.eso.org/public/chile/about-eso/vision-mission/

[15] Report on ESO's benefits to society: https://www.eso.org/public/products/brochures/brochure_0076/

Note

[a] Current Member States of ESO are: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

This artist's rendering shows a night view of ESO's Extremely Large Telescope in operation on Cerro Armazones in northern Chile. The telescope is shown using lasers to create artificial stars high in the atmosphere.

ESO/L. Calçada

Astronomical Science

This three-colour composite image of the Omega Nebula (Messier 17, or NGC 6618), is based on images obtained with the EMMI instrument on the ESO 3.58-metre New Technology Telescope at the La Silla Observatory. It spans an angle equal to about one third the diameter of the Full Moon, corresponding to about 15 light-years at the distance of the Omega Nebula.

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ESPRESSO Probes the Fine-structure Constant

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[19] INAF–Astrophysical Observatory of Turin, Italy

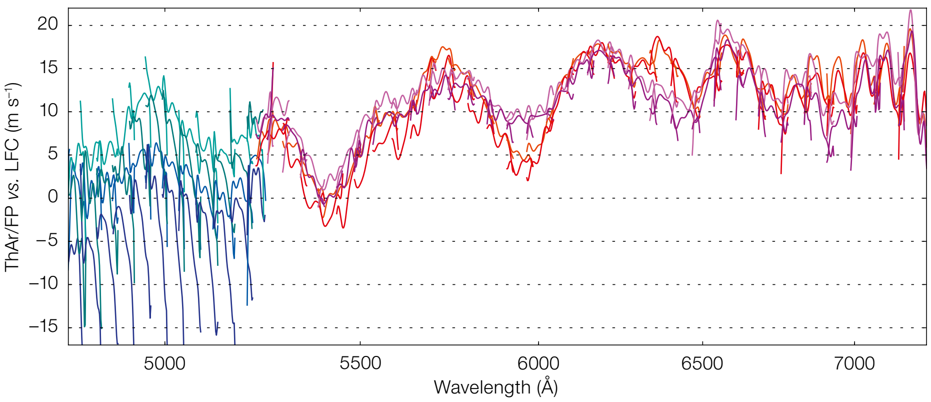

Figure 1. Comparison of the ThAr/FP and LFC calibrations. Colours indicate different fibres and slices for the Red and Blue CCDs (from Schmidt et al., 2021). Light and dark blue are slices a and b of Fibre A respectively, and light and dark green are slices a and b of Fibre B respectively, for the blue CCD. The two shades of orange are slices a and b of Fibre A, while the two shades of violet are slices a and b of Fibre B for the red CCD. For validation the sampling is reduced to 100 km s^{-1}. Traces when the blaze function drops below 25% of the peak throughput are excluded.

The Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) is the new high-resolution spectrograph of ESO's Very Large Telescope. It was designed for ultra-high radial-velocity precision and extreme spectral fidelity with the aim of performing exoplanet research and fundamental astrophysical experiments with unprecedented precision and accuracy. The first precise ESPRESSO constraint on cosmological variations in the fine-structure constant has been obtained recently by using the laser frequency comb to provide a highly accurate wavelength scale. The target was the famous quasar HE 0515-4414, one of the brightest in the southern sky, with an intervening galaxy at $z = 1.15$ which imprints metal absorption lines onto the spectrum. The lack of velocity shifts between these lines is consistent with the absence of cosmological variation in the fine-structure constant at the level of about 1 part per million.

Introduction

In the Standard Model of particle physics the strengths of fundamental physical interactions are described through dimensionless couplings. Historically, these have been assumed to be constant. However, they are known to change with energy, and in many extensions of the Standard Model they will also change in time and possibly in space (Martins, 2017). The fine-structure constant, $\alpha = e^2/\hbar c$, is a dimensionless fundamental constant that can be probed directly with spectroscopic techniques because the frequencies of spectral lines depend on α in different ways. In laboratories, comparing atomic clocks based on different transitions over timescales of a few years has provided extraordinarily precise limits on local time variations in α of just 1×10^{-18} per year (Lange et al.,

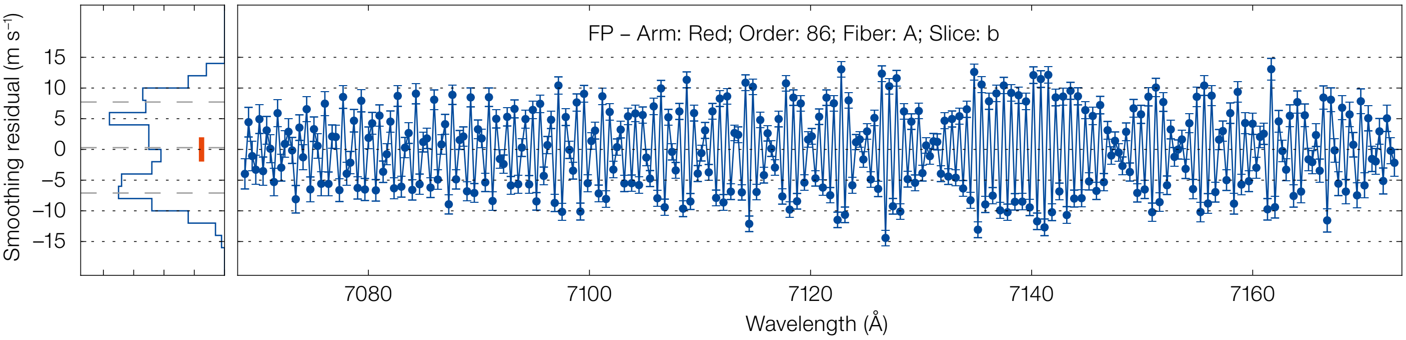

Figure 2. Alternate positional deviations up to +/– 10 m s^{-1} in the location of individual FP lines from the standard wavelength solution (from Schmidt et al., 2021). This is also seen in the LFC exposures. The effect is stable in time and it may also affect the science spectra. Thus, every individual line measurement is affected by 5–8 m s^{-1} correlated noise.

2021). While it may be tempting to extrapolate such constraints linearly to cosmological time, it should be emphasised that how the fundamental constants may vary, and on what this may depend, is entirely unknown. Instead, the variability or constancy of α must be explicitly tested over the full range of time (and distance) scales available to experiments.

The most effective way to probe cosmological variations in α is the many-multiplet (MM) method which measures the wavelength shifts of many different transitions from several atomic species produced in intervening quasar absorption systems (Dzuba, Flambaum & Webb, 1999a,b; Webb et al., 1999). Transitions from different multiplets often have very different dependencies on α. So measuring the velocity shifts between these transitions in a quasar absorption system provides a direct probe of $\Delta\alpha/\alpha$ — the relative difference between α in the absorber (α_{abs}) and its current laboratory value on Earth (α_{lab}):

$$\Delta\alpha/\alpha = (\alpha_{abs} - \alpha_{lab}) / \alpha_{lab} \cong -(\Delta v/c)\ (1/2Q)$$

where Δv is the velocity shift caused by a small variation in α (Dzuba et al., 2002). Here, Q is the sensitivity coefficient, namely the expected sensitivity of the transition's laboratory frequency to variations in α. These Q coefficients have been calculated using several different many-body quantum mechanical techniques (see, for example, Dzuba, Flambaum & Webb, 1999a,b; Murphy & Berengut, 2014). For typical values of Q (–0.03 to 0.05), a variation of one part per million (ppm) in α would produce a velocity shift Δv ~ 20 m s^{-1} between different transitions from different multiplets and atoms or ions.

The MM method has been widely used to measure $\Delta\alpha/\alpha$ at high redshifts, the largest samples being obtained with archival spectra from two high-resolution spectrographs: the Ultraviolet and Visual Echelle Spectrograph (UVES) at the Very Large Telescope (VLT) and the HIgh Resolution Echelle Spectrometer (HIRES) at the Keck Observatory (see, for example, Webb et al., 2001; Murphy, Webb & Flambaum, 2003; Webb et al., 2011). Each sample showed tentative detections of a variation in α at about the 5 ppm level, but in opposite senses. King et al. (2012) combined the sample of 143 Keck/HIRES absorption systems with a sample of 154 from VLT/UVES to produce a data set of $\Delta\alpha/\alpha$ measurements in 293 distinct absorption systems. The combined results showed a statistical preference for a dipolar spatial variation of α across the sky at about the 10 ppm level with greater than 4σ statistical significance. Note that a theoretical model which can account for a spatial dipole with such a low amplitude is more difficult to identify than one in which α varies with time (see, for example, Olive, Peloso & Uzan, 2011). As should be expected for such a surprising result, many authors have questioned the data, analysis, assumptions and potential systematic errors underpinning these measurements, and some have presented alternative data sets and analyses (for example, Chand et al., 2004; Quast, Reimers & Levshakov, 2004; Levshakov et al., 2005, 2007; Molaro et al., 2008). Constraints from higher-quality spectra of individual absorbers were also obtained, but none of them directly supported or strongly conflicted with the α dipole evidence (Molaro et al., 2013; Bainbridge & Webb, 2017; Wilczynska et al., 2020).

It now appears likely that the initial evidence for cosmological variations in α arose from a problem common to all slit-based spectrographs. Distortions in the wavelength scale of the quasar spectra were discovered when observing solar spectra reflected from asteroids with UVES, and after comparing them with an accurately calibrated solar spectrum from a Fourier-transform spectrometer (Rahmani et al., 2013). These distortions were found to be ubiquitous in slit-based echelle spectrographs (UVES, HIRES, and the High Dispersion Spectrograph [HDS] at the Subaru Telescope) and substantial enough to explain the quasar absorption results (Whitmore & Murphy, 2015; cf. Dumont & Webb, 2017). Recent quasar observations with UVES, HIRES and HDS, dedicated to measuring α and explicitly correcting for these distortions, are inconsistent with the earlier results and show no variations in α (Evans et al., 2014; Murphy, Malec & Prochaska, 2016; Murphy & Cooksey, 2017; Kotuš, Murphy & Carswell, 2017). On balance, there is currently no compelling evidence for variations in α over cosmological time or distance scales. Nevertheless, even when accurate corrections for distortions are possible, the uncertainty in the wavelength calibration of slit-based spectrographs dominates the error budget.

ESPRESSO enters the game

The Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO; Pepe et al., 2021) was specifically designed to suppress wavelength calibration errors in quasar absorption measurements of α

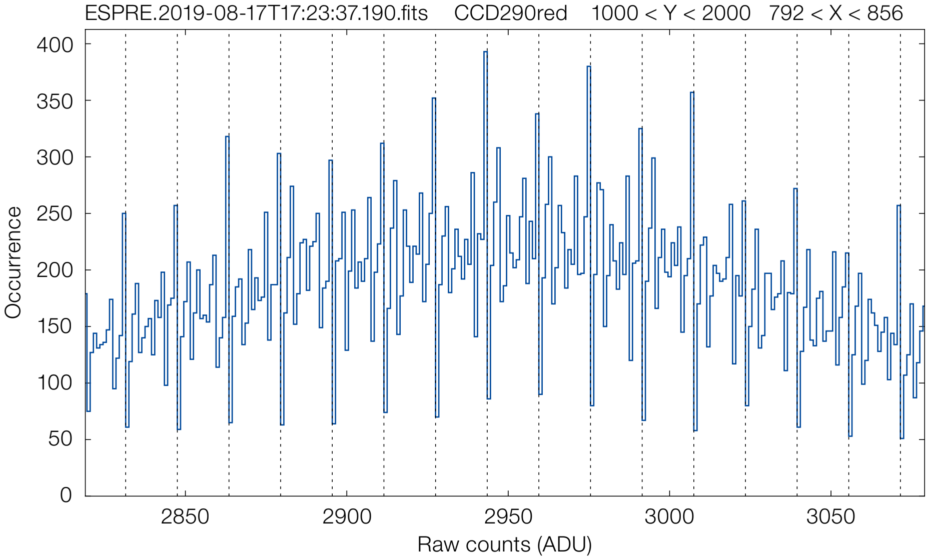

Figure 3. Example of the nonrandom occurrence of pixel values in a region of a LED frame around 7546 Å. This is probably a manifestation of the binary offset effect discovered by Boone et al. (2018) in the CCDs of several major facilities.

(Molaro, Murphy & Levshakov, 2006; Molaro, 2009). The spectrograph is located in the incoherent Combined-Coudé Laboratory underneath the four Unit Telescopes (UTs) of the VLT, and can be fed by any one UT or all four simultaneously. ESPRESSO is fed by optical fibres, is sealed in a stable vacuum vessel with temperature control at the millikelvin level, and can be calibrated with an 'astrocomb' — a femtosecond-pulsed laser frequency comb (LFC). The high frequency-space density of uniformly separated comb modes, whose individual frequencies are known *a priori* with extremely high accuracy, could enable centimetre-per-second (photon-limited) calibration precision (Murphy et al., 2007; Milaković et al., 2020). The ESPRESSO astrocomb covers the wavelength range 4850–7000 Å of ESPRESSO's full 3781–7874 Å range, and provides an accuracy of approximately 1 m s^{-1} for velocity shifts between transitions in the spectrum of the quasar HE 0515-4414. This is well below the statistical precision of the quasar absorption measurements themselves (about 30 m s^{-1}), so ESPRESSO effectively removes wavelength calibration from the error budget. While only a few LFC calibration exposures could be obtained for HE 0515-4414, they were sufficient for these purposes.

In Figure 1 the comparison of ESPRESSO's LFC and standard ThAr+Fabry-Perot (FP) calibrations made by Schmidt et al. (2021) is shown, revealing a wavy structure. These distortions are most likely due to the standard ThAr+FP calibration used by the data reduction software. In principle, these could affect other measurements of $\Delta\alpha/\alpha$ with ESPRESSO if only ThAr+FP calibration were used and no corrections were made with solar twin or asteroid exposures. A further effect has also been found in the LFC and FP spectra, as shown in Figure 2. The wavelength calibration residuals of alternate, individual FP (or LFC) lines are strongly anti-correlated in ESPRESSO. The origin of this effect is unclear. Nor is it clear whether this affects the science exposures as well.

Another discovery, which we report here for the first time, concerns the flux, namely the detection of the binary offset effect (see Boone et al., 2018) on some of the amplifiers of the ESPRESSO CCDs. The example in Figure 3 shows the nonrandom occurrence of pixel values. This results in flux anomalies at the 1% level in the spectral range covered by the affected amplifiers. The underlying mechanism seems to be correlated with the number of "1" bits in the binary representation of the pixel value, just as found by Boone et al. (2018) in the CCDs of many instruments in major ground- and space-based telescopes.

Observations and data analysis

HE 0515-4414 was identified as a very bright (Gaia G = 14.9 mag) quasar at redshift z_{em} = 1.71 by Reimers et al. (1998). It was observed during the ESPRESSO Consortium's Guaranteed Time Observations (GTO) in two main runs: a visitor-mode run on 4–7 November 2018, and service-mode observations between November 2019 and March 2020. The total integration of 57 916 s (16 h) was obtained over 17 exposures. The high-resolution, single-UT mode with 2-pixel binning in the spatial direction (i.e., 'singleHR21') was selected, providing a nominal resolving power of R ~ 145 000 with a 1-arcsecond-diameter fibre. All exposures were obtained with UT3-Melipal, except for those in November 2019 which were observed with UT1-Antu. Single exposures were reduced with the standard ESPRESSO data reduction software (v. 2.2.3) and combined with UVES_POPLER (v. 1.05; Murphy et al., 2019) to form a single spectrum (S/N ~ 105 per 0.4-km s^{-1} pixel at 6000 Å).

In Figure 4 the UVES and HARPS spectra for three representative transitions are compared with the new ESPRESSO spectrum. The high R and signal-to-noise ratio revealed that the z_{abs} = 1.1508 absorption system was more complex than previous studies had found: strong constraints on the relative optical depths of two different Mg I lines confirmed the presence of very narrow velocity components in the strongest absorption feature (Doppler b < 0.5 km s^{-1}). A total of 129 velocity components were required to fit the approximately 720-km s^{-1}-wide absorption profile, which was split into three 'regions' for simplicity, with the strongest Mg I and Fe II transitions providing the main constraints on $\Delta\alpha/\alpha$ in the reddest region.

In Figure 5 the strong lines in the reddest regions are shown to illustrate the model fitting. The entire analysis procedure was developed using a blinded approach to avoid human biases. Table 1 summarises the fiducial fitting results with the 1σ statistical and systematic uncertainties for each of the three regions. The weighted mean result for the entire absorber is:

$$\Delta\alpha/\alpha = 1.3 \pm 1.3_{\mathrm{stat}} \pm 0.4_{\mathrm{sys}}\ \mathrm{ppm},$$

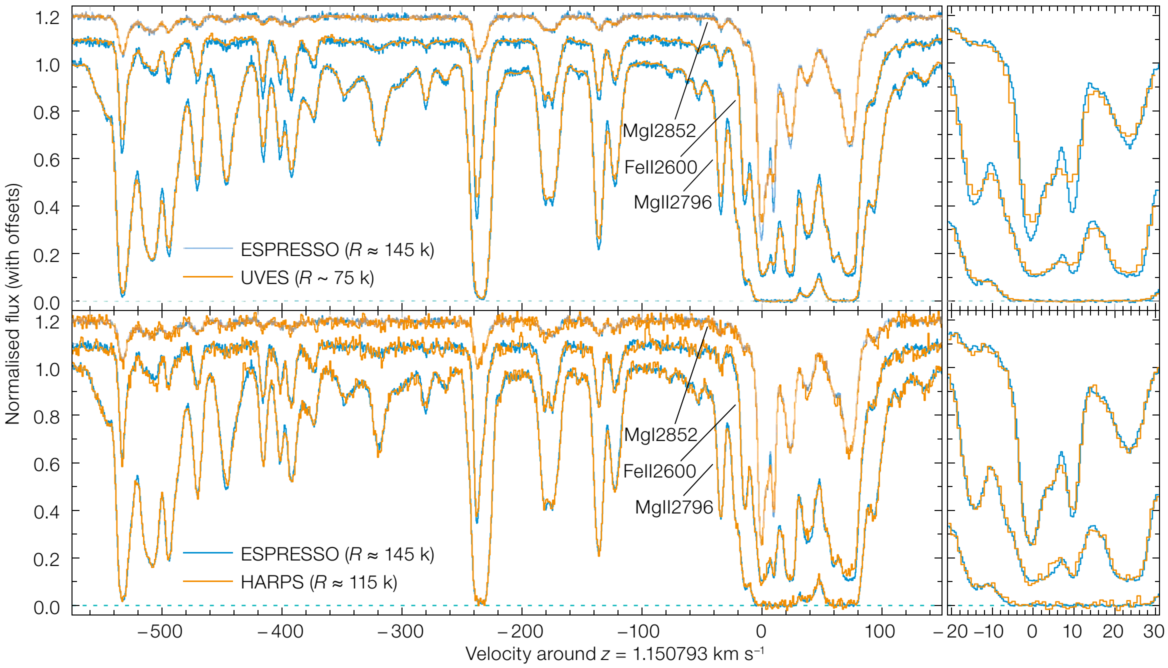

Figure 4. The upper panels compare ESPRESSO (blue) and UVES (orange) spectra, while the lower panels compare the ESPRESSO (blue) and HARPS (orange) spectra (from Murphy et al., 2022). The three spectra in each panel indicate Mg I 2852 Å, Fe II 2600 Å and Mg II 2796 Å, respectively, offset by 10% in flux for clarity. The right-hand panels zoom-in on the features near 0 and 9 km s^{-1}.

with 1σ statistical and systematic error components. The result is consistent with no change in the fine-structure constant between the absorber at $z_{\mathrm{abs}} = 1.1508$ and the current laboratory value.

Our total uncertainty, 1.4 ppm, is similar to the ensemble precision of the previous large samples of absorbers from HIRES and UVES that indicated variations at about the 5 ppm level (Webb et al., 2001; Murphy, Webb & Flambaum, 2003; Murphy et al., 2004; Webb et al., 2011; King et al., 2012), which likely arose from long-range distortions in the wavelength scale (Rahmani et al., 2013; Whitmore & Murphy, 2015). Even the more recent results, which were corrected for these effects, had residual wavelength calibration uncertainties of 0.5–3.5 ppm, larger than our total systematic error budget (Evans et al., 2014; Murphy & Cooksey, 2017). Kotuš, Murphy & Carswell (2017) corrected the wavelength scale of their UVES spectrum of HE 0515-4414 by using the High Accuracy Radial velocity Planet Searcher (HARPS) spectrum of the same quasar. However, this still left about a 0.6 ppm wavelength calibration uncertainty which dominated their systematic error budget. The recent measurement in the same absorber by Milakovic et al. (2021) used an LFC-calibrated HARPS spectrum to measure $\Delta\alpha/\alpha$, thereby avoiding wavelength calibration uncertainties, just like our ESPRESSO measurement. Of course, the lower S/N of the HARPS spectrum (~ 58 per km s^{-1}, cf.

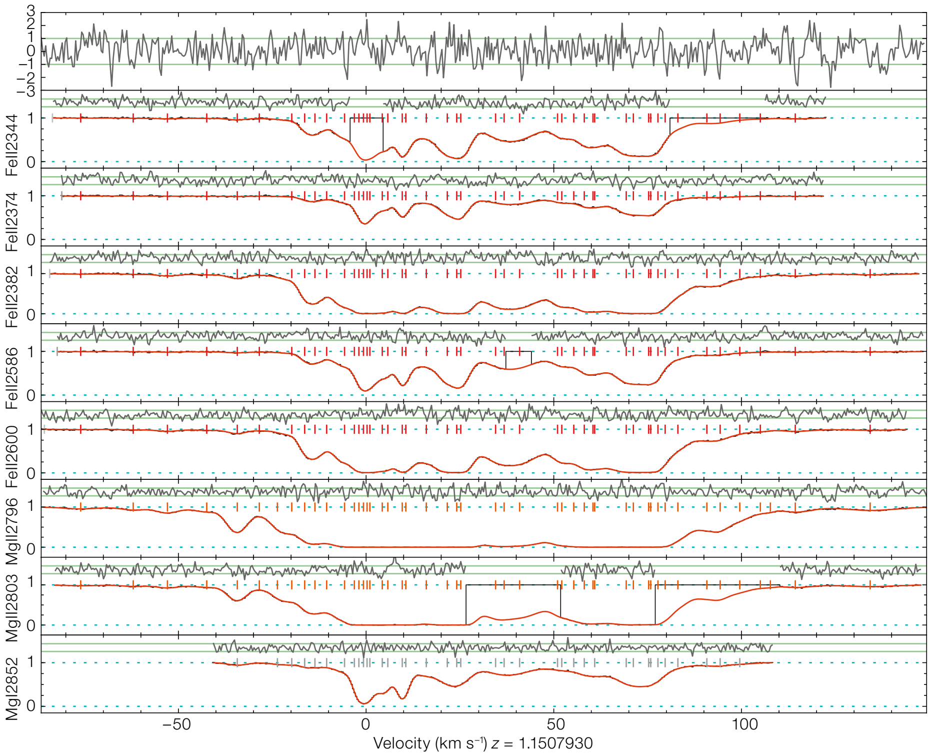

Figure 5. Example of an ESPRESSO spectrum (black histogram) for some strong transitions labelled on the vertical axis of the $z_{\mathrm{abs}} = 1.1508$ absorber (from Murphy et al., 2022). The fiducial model is shown with a red line, with individual components indicated by tick-marks. The residuals between the data and the model, normalised by the uncertainties, are shown above each transition.

170 for our ESPRESSO spectrum) limited the precision to 2.4 ppm. By contrast, our measurement is effectively free from systematic wavelength calibration errors thanks to the specific design features of ESPRESSO to suppress them (for example, the octagonal fibre feed, stable vacuum environment, and LFC calibration). This means our total systematic uncertainty is well below our photon-statistical uncertainty — a remarkable change from the pre-ESPRESSO era! Our main systematic uncertainties arise from ambiguities in fitting the absorption profile, from effects from redispersion of the spectra, and from convergence of the fitting procedure.

Our new $\Delta\alpha/\alpha$ measurement is consistent with the recent UVES and HARPS measurements in the same absorber (see above), and also the 26 other recent measurements in other absorbers with HIRES, UVES and HDS where the wavelength distortions were corrected, or had no significant impact. Combining these 28 independent measurements with low calibration error with our new ESPRESSO measurement provides a weighted mean

$$\Delta\alpha/\alpha = -0.5 \pm 0.5_{\mathrm{stat}} \pm 0.4_{\mathrm{sys}}\ \mathrm{ppm}.$$

The above combined result is still dominated by the single UVES measurement in HE 0515-4414 by Kotuš, Murphy & Carswell (2017). However, the ESPRESSO era has arrived, and it promises to provide a larger sample of well-calibrated, high-quality quasar absorption spectra for measuring $\Delta\alpha/\alpha$ through the instrument consortium's GTO and open, competitive observing time. One important outstanding problem with improving quasar absorption measurements of $\Delta\alpha/\alpha$ is the lack of observational constraints on how the isotopic abundances in the absorbers differ from the terrestrial values. ESPRESSO's higher resolving power offers an opportunity to directly constrain or measure the Mg isotopic abundances, in particular absorption systems where the velocity structure is rather simple.

Constraints on theoretical models

The new bound on α significantly improves constraints on cosmological models with a varying α. Broadly speaking, these can be divided into two classes (Martins, 2017). In the first class, the electromagnetic sector is coupled to a scalar field which simultaneously provides the dark energy responsible for the acceleration of the Universe (Martins et al., 2022; da Fonseca et al., 2022). In the second class, dark energy and a varying α stem from different physical mechanisms, the simplest example being Bekenstein models (Martins et al., 2022). In both cases, the new constraints are consistent with a null variation of the field, i.e., compatible with ΛCDM, and we have improved previous constraints by more than a factor of ten. Although this gain is dominated by recent improvements in local atomic clock tests, the astrophysical measurements do help to break the degeneracies between cosmology and fundamental physics parameters, particularly in the first class of models. Additional ESPRESSO bounds on α will also enable improved constraints on theoretical models with spatial or environmental dependencies.

Region	Left	Central	Right	Combined
$\Delta\alpha/\alpha$	2.17	1.57	1.14	1.31
1σ statistical uncertainty	3.31	5.59	1.45	1.29
Systematic uncertainty	1.35	2.37	0.45	0.43

Table 1. Results for the three different regions of the absorber with 1σ statistical uncertainties together with the likely systematic errors from several possible sources. See Murphy et al. (2022) for further details of the different entries.

Acknowledgements

We dedicate this work to the memory of Dieter Reimers (1943–2021), discoverer of the quasar HE 0515−4414, leader in European astronomy, colleague and friend to many authors of this paper. MTM acknowledges the support of the Australian Research Council through Future Fellowship grant FT180100194. The work of CJAPM was funded by FEDER through COMPETE 2020 (POCI), and by Portuguese funds through FCT through project POCI-01-0145-FEDER-028987 and PTDC/FIS-AST/28987/2017; the author also acknowledges FCT and POCH/FSE (EC) support through Investigador FCT Contract 2021.01214.CEECIND/CP1658/CT0001. NJN was funded by projects POCI-01-0145-FEDER-028987, PTDC/FIS-AST/28987/2017, PTDC/FIS-AST/0054/2021 and EXPL/FIS-AST/1368/2021, as well as UIDB/04434/2020 & UIDP/04434/2020, CERN/FIS-PAR/0037/2019, PTDC/FIS-OUT/29048/2017.DM is also supported by the INFN PD51 INDARK grant.

References

Bainbridge, M. B. & Webb, J. K. 2017, MNRAS, 468, 1639
Boone, K. et al. 2018, PASP, 130, 064504
Chand, H. et al. 2004, A&A, 417, 853
da Fonseca, V. et al. 2022, to appear in A&A, arXiv:2204.02930
Dumont, V. & Webb, J. K. 2017, MNRAS, 468, 1568
Dzuba, V. A., Flambaum, V. V. & Webb, J. K. 1999a, Phys Rev A, 59, 230
Dzuba, V. A., Flambaum, V. V. & Webb, J. K. 1999b, Phys Rev Lett, 82, 888
Dzuba, V. A. et al. 2002, Phys Rev A, 66, 022501
Evans, T. M. et al. 2014, MNRAS, 445, 128
Lange, R. et al. 2021, Phys Rev Lett, 126, 011102
Levshakov, S. A. et al. 2005, A&A, 434, 827
Levshakov, S. A. et al. 2007, A&A, 466, 1077
King, J. A. et al. 2012, MNRAS, 422, 3370
Kotuš, S. M., Murphy, M. T. & Carswell, R. F. 2017, MNRAS, 464, 3679
Martins, C. J. A. P. 2017, Rep Prog Phys, 80, 126902
Martins, C. J. A. P. et al. 2022, Phys Rev D, 105, 123507
Milaković, D. et al. 2020, MNRAS, 493, 3997
Milaković, D. et al. 2021, MNRAS, 500, 1
Molaro, P., Murphy, M. T. & Levshakov, S. A. 2006, IAU Symp, 232, 198
Molaro, P. et al. 2008, EPJST, 163, 173
Molaro, P. 2009, in Astrophysics and Space Science Proceedings, *Science with the VLT in the ELT Era*, ed. Moorwood, A., (Dordrecht: Springer), 389
Molaro, P. et al. 2013, A&A, 555, A68
Murphy, M. T., Webb, J. K. & Flambaum, V. V. 2003, MNRAS, 345, 609
Murphy, M. T. et al. 2004, in Lecture Notes in Physics, 648, *Astrophysics, Clocks and Fundamental Constants*, ed. Karshenboim, S. G. & Peik, E., (Berlin, Heidelberg: Springer), 13
Murphy, M. T. et al. 2007, MNRAS, 380, 839
Murphy, M. T. & Berengut, J. C. 2014, MNRAS, 438, 388
Murphy, M. T., Malec, A. L. & Prochaska, J. X. 2016, MNRAS, 461, 2461
Murphy, M. T. & Cooksey, K. L. 2017, MNRAS, 471, 4930
Murphy, M. T. et al. 2019, MNRAS, 482, 3458
Murphy, M. T. et al. 2022, A&A, 658, A123
Olive, K. A., Peloso, M. & Uzan, J.-P. 2011, Phys Rev D, 83, 043509
Pepe, F. et al. 2021, A&A, 645, A96
Quast, R., Reimers, D. & Levshakov, S. A. 2004, A&A, 415, L7
Reimers, D. et al. 1998, A&A, 334, 96
Rahmani, H. et al. 2013, MNRAS, 435, 861
Schmidt, T. M. et al. 2021, A&A, 646, A144
Webb, J. K. et al. 1999, Phys Rev Lett, 82, 884
Webb, J. K. et al. 2001, Phys Rev Lett, 87, 091301
Webb, J. K. et al. 2011, Phys Rev Lett, 107, 191101
Whitmore, J. B. & Murphy, M. T. 2015, MNRAS, 447, 446
Wilczynska, M. R. et al. 2020, Science Advances, 6, 9672

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The Core of the Matter — Spatially Resolving Active Galactic Nuclei with GRAVITY

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Thanks to the superb sensitivity and resolution of GRAVITY, ESO’s near-infrared beam combiner for the Very Large Telescope Interferometer, our Large Programme study of the inner regions of active galactic nuclei (AGN) has delivered several recent breakthroughs. We have spatially resolved the broad line region (BLR) for three nearby AGN, supporting the rotating disc model, directly measuring the masses of their supermassive black holes (SMBHs), and testing the BLR radius-luminosity (*R*–*L*) scaling relation. We have measured the hot dust sizes for eight AGN and fully imaged the hot dust structure for two AGN. Our dust sizes also test the hot dust *R*–*L* scaling relation, revealing the first evidence for luminosity-dependent deviations from the expected relation. The novel GRAVITY data provide unique insight into the physics around SMBHs. In addition, they test the basic assumptions behind mass measurements based on the *R*–*L* scaling relation and reverberation mapping, which is currently the only method for measuring black hole masses in large surveys and out to high redshift. Our observations provide an entirely new, independent method for measuring SMBH masses. With GRAVITY+, we will be able to vastly expand to both larger samples and higher redshifts with the ultimate goal of tracing black hole growth and galaxy coevolution through cosmic time.

The circumnuclear environment of AGNs

Since their discovery in the 1960s astronomers have wanted to know what exactly goes on in the nuclei of quasars (or more generally in active galactic nuclei [AGN]). It became clear early on that AGN come in many different flavours, constituting a veritable zoo of AGN phenomenology. For instance, Type 1 AGN show very broad emission lines in their spectra (with widths of several 1000 km s^{-1}), while Type 2 AGN have only narrow emission lines. Studies in the late 1980s and early 1990s (for example, Antonucci & Miller, 1985) suggested that the different AGN flavours were not due to fundamental intrinsic differences or to evolution, but that perhaps many AGN are the same except for orientation effects. For example, Type 2 AGN often show broad emission components in polarised light, i.e., in light scattered from clouds further out. In Type 2 AGNs the direct view of the broad-line region (BLR) would then be blocked by some dusty structure (often referred to for historical reasons as “the torus”).

Obscuring dust and a broad-line emitting region are thus two fundamental ingredients of most contemporary AGN models. If we attribute the enormous widths of broad emission lines to the Doppler motion of gas clouds, then motion in the deep gravitational potential of the central SMBH is the likely explanation. The high velocities and the fact that the BLR is unresolved in high-resolution images and varies rapidly in brightness all suggest that the BLR must be very close to the SMBH. But despite their importance as a hallmark feature of AGN, and although BLRs have been studied for almost 60 years, many basic properties like structure, kinematics and inclination remain elusive. In some models the BLR arises as continuous, outflowing gas distribution in an accretion-disc wind. Other models employ large numbers of small gas clouds, for instance in a spherical or disc-like distribution. The BLR clouds might originate in torus clumps that col-

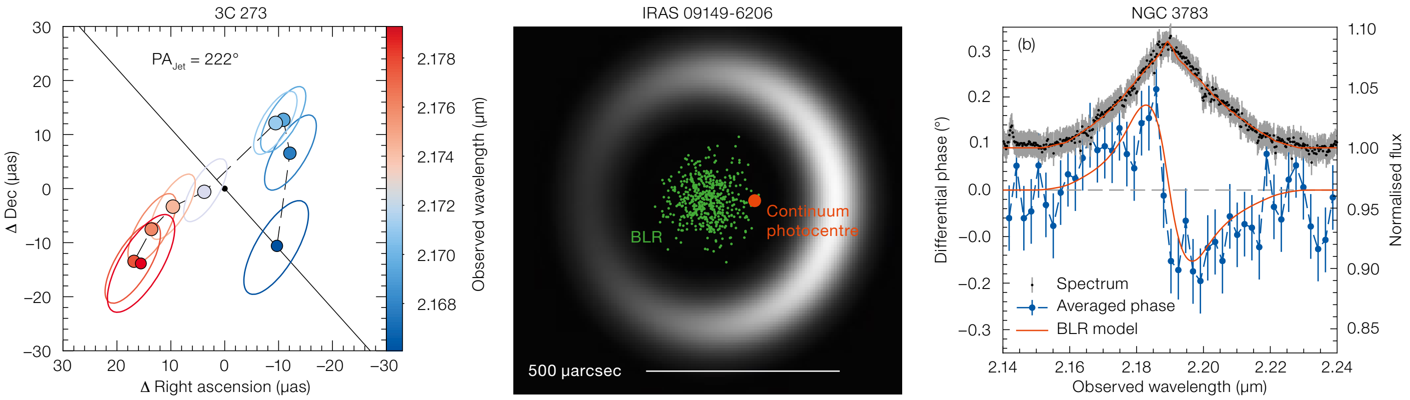


Figure 1. Left: Observed velocity-resolved photocentres for 3C 273 indicating a kinematic axis nearly perpendicular to the radio jet axis (black line) (GRAVITY Collaboration et al., 2018). Middle: Cartoon illustrating a possible cause of the observed offset between the near-infrared continuum photocentre and the BLR for IRAS 09149-6206 (GRAVITY Collaboration et al. 2020c). Right: Observed BLR differential phase signal (a signature of the photocentre distribution) for NGC 3783 (blue points) together with the best-fit model (red lines) and emission line flux profile (black points) (GRAVITY Collaboration et al., 2021a).

lide, get scattered inside the sublimation radius and are then disrupted. Or, perhaps, is the BLR just the puffed-up inner edge of the torus (see, for example, Baskin & Laor, 2018; Wang et al., 2017)?

Measuring SMBH masses

This lack of understanding of the true nature of these components is, to say the least, very unfortunate. Accurate knowledge of the size, distribution and kinematic properties of the BLR gas would not only constrain the transport mechanism of material onto the accretion disc and into the jet or the onset of outflows, but also provide more precise black hole mass measurements.

To date, studies of the BLR structure have relied mostly on reverberation mapping (RM). The reverberation technique uses the time variability observed in the AGN continuum emission (from the accretion disc) and the subsequent response of the gas in the BLR. The time delay between continuum and BLR gas emission translates directly into a radius for the BLR. The width of the BLR lines, assuming the BLR consists of clouds moving in the gravitational potential of the SMBH, provides the velocity of these clouds. Black hole masses can then be inferred from these two observations via the virial theorem. Importantly, RM programmes established a size-luminosity (R–L) relation ($R_{BLR} \sim L^{\alpha}$; for example, Dalla Bontà et al., 2020; Kaspi et al., 2000), that allows black hole mass estimates even from a single AGN spectrum (and a measurement of the AGN luminosity). This is the only available method for measuring black hole masses in large surveys and out to high redshift and plays a key role in our understanding of black hole growth over cosmic time.

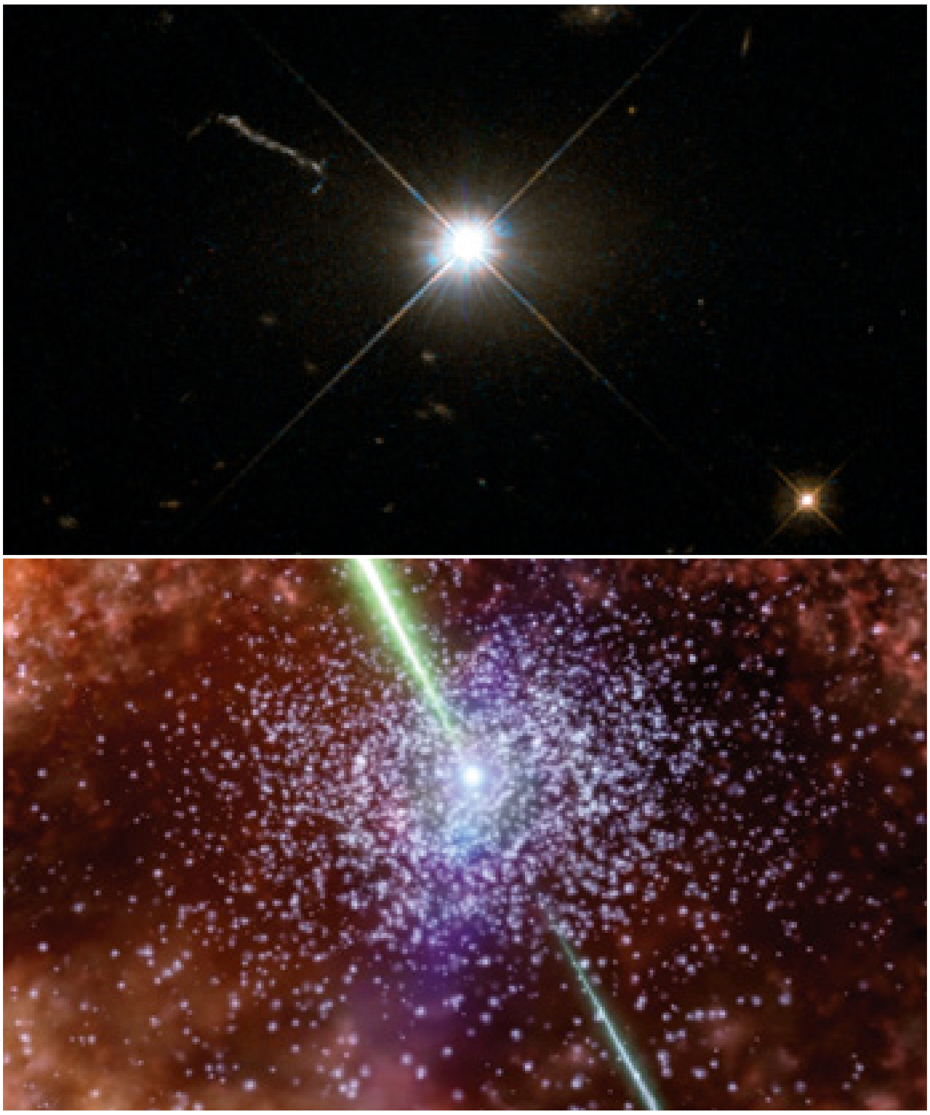
However, the method has well-known limitations: the inclination and the detailed velocity field of the BLR are very hard to extract from RM data. Moreover, recent investigations of the R–L relationship suggest that a third parameter must be taken into account, the Eddington ratio (i.e., the SMBH accretion rate relative to the theoretical maximum for a given black hole mass). Application to AGN at higher redshift requires the assumption that the locally calibrated R–L relation still holds at high redshift. The general approach taken towards these uncertainties has been, in the absence of other data, to absorb them into the black hole mass uncertainties. Typically, it is assumed that AGN follow the same M_{BH}–σ relation as quiescent galaxies, and this provides a calibration of the AGN black hole mass scale.

Obviously, better knowledge of the BLR size, kinematics, and orientation, from direct constraints bypassing the R–L and M_{BH}–σ relations, is crucial for improving our understanding of all AGN black hole masses and their uncertainties. In turn, this would advance our understanding of the evolution of black holes over cosmic time. This is a primary goal of the GRAVITY AGN programme.

The GRAVITY AGN Large Programme

GRAVITY, the near-infrared beam combiner for the Very Large Telescope Interferometer (VLTI), provides images with 3-milliarcsecond angular resolution as well as 10-microarcsecond astrometric accuracy in the range 1.98 to 2.40 μm. Spectro-astrometry (SA) with GRAVITY provides a new, direct probe of the BLR spatial and velocity structure which can independently test and break degeneracies in RM studies. This technique measures the flux-weighted spatial offset from the continuum of each velocity channel across an emission line (Figure 1, left). In interferometry such spatial offsets result in phase differences in the fringe pattern, which can be measured very precisely. In this way, precise phase measurements from interferometric SA provide spatial information on scales much smaller than the interferometric beam. Combining the six independent VLTI baselines, we can then kinematically model the velocity structure of the BLR (Figure 1, right) and measure both the BLR radius and, ultimately, the SMBH mass.

We achieved the first demonstration of the power of SA in this context in 2018, by spatially resolving a velocity gradient across the BLR of the quasar 3C 273 (z = 0.158, Figure 2, GRAVITY Collaboration et al., 2018). The gradient revealed rotation perpendicular to the jet, and is



ESA/Hubble & NASA

ESO/L. Calçada

Figure 2. Top: Hubble Space Telescope image of the quasar 3C 273. Bottom: Zooming in, we are now able to spatially resolve the BLR, where gas clouds whirl around the central black hole and a jet of material is ejected at high speeds from the black hole's poles (artist's impression).

consistent with line emission from a thick disc of gravitationally bound material around a black hole of 3×10^8 solar masses. We measured a disc radius of 150 light-days confirming the size of 130–200 light-days derived from RM.

Following up on this exciting result (resolving a structure of the size of ~ 0.15 pc at a distance of 550 Mpc!) we have been granted by ESO an open-time Large Programme (17 nights over 4 semesters, starting in April 2019) to observe with VLTI/GRAVITY 11 nearby AGN that span four orders of magnitude in luminosity. GRAVITY's exquisite performance opened the door to resolving the innermost regions of the brightest AGN: the BLR and surrounding hot dust. Through our Large Programme we address three key questions: How reliable are RM-based BLR sizes and black hole masses? Are BLR kinematics always dominated by ordered rotation? What are the size and shape of the obscuring structure? We further aim to establish a new, GRAVITY-based R–L relation to form the basis for more robust black hole mass measurements in large samples in both the local and distant Universe.

Resolving the broad-line region

The Large Programme has already yielded two further published spectro-astrometric BLR measurements, for IRAS 09149−6206 and NGC 3783. Our study of IRAS 09149−6206, a Type 1 AGN at $z = 0.0573$, led to a much-improved phase calibration method that reduced the instrumental uncertainty of the differential phase to better than 0.05 deg per spectral channel in each baseline[a]. Armed with the improved data reduction, we significantly detected the BLR differential phase signal across the hydrogen Br-γ line. Surprisingly, the signal primarily represented a systematic offset of ~ 120 microarcseconds (0.14 pc) between the BLR and the centroid of the hot dust distribution traced by the 2.3-μm continuum. This offset is well within the dust sublimation region, which matches the measured ~ 300-microarcsecond (0.35 pc) diameter of the continuum and can be explained by an asymmetric hot dust continuum such that the photocentre of the continuum is shifted towards the brightest side of the dust structure (see middle panel of Figure 1). Including this effect in our BLR model, we then measured a BLR size of 65 microarcseconds (0.075 pc) and SMBH mass of 1×10^8 solar masses (Gravity Collaboration et al., 2020c).

In NGC 3783, a galaxy only ~ 40 Mpc away that hosts a bright Type 1 AGN, we again detected the BLR differential phase signal (see right panel of Figure 1). The systematic offset to the continuum is smaller than for IRAS 09149−6206, thus enhancing the rotational signature. For this AGN, we measure a BLR size of 71 microarcseconds (0.013 pc) and SMBH mass of 5×10^7 solar masses. In this case, the physical BLR size is almost a factor of two larger than the one measured by RM, and is consistent with a radial distribution of clouds that peaks in the inner regions but is significantly extended to large radii. This brings to light a discrepancy between RM measurements — which are variability-weighted and thus biased towards the inner regions — and interferometric measurements — which are flux-weighted and more sensitive to outer radii (GRAVITY Collaboration et al., 2021a).

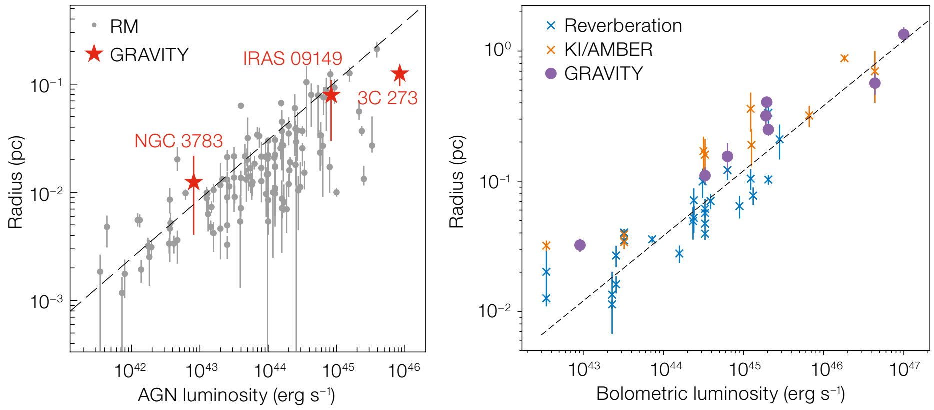


Figure 3. Left: BLR *R*–*L* relation with our new GRAVITY measurements (red) plotted with RM data points (grey points) and RM relation (black dashed line) (GRAVITY Collaboration et al., 2021a). Right: Hot dust *R*–*L* relation with our new GRAVITY measurements. Our interferometric hot dust sizes match previous Keck interferometer sizes. They seem to follow a flatter relationship than $R \propto L^{0.5}$ (which would be the expected relationship if hot dust radiation peaks near the dust sublimation radius) (GRAVITY Collaboration et al., 2020b).

With these published BLR size measurements, we have begun constructing our own GRAVITY-based *R*–*L* relation. The left panel of Figure 3 shows as red stars the locations of our measurements compared to the RM-based measurements and relation (grey points with black dashed line). We begin to see the recently observed deviation towards smaller size in high-luminosity AGN that may be partly due to the high accretion rate (GRAVITY collaboration et al., 2021a). From the Large Programme we have BLR data for another four AGN that are under analysis and will be used to expand our GRAVITY-based BLR *R*–*L* relation.

Imaging and sizing-up the innermost hot dust

Another long-standing issue of AGN models is the size and structure of the obscuring, dusty region: is it a torus or a disc, clumpy or not, inflowing or outflowing? The near- and mid-infrared luminosity associated with AGN originates in dust surrounding the AGN and heated by it. However, like the BLR, the innermost circumnuclear dust emission cannot be resolved in single-dish images. In the past decade infrared interferometry has begun to shed light on the physical structure of this component. Tens of AGN have been observed in the mid-infrared with the MID-infrared interferometric Instrument (MIDI) at the VLTI. Detailed results from Circinus and NGC 1068 show evidence for an inner disc, but have also revealed dust in the polar regions indicative of outflow (López-Gonzaga et al., 2016). The presence of multiple components could have a severe impact on dust-RM methods that assume a torus origin. The near-infrared is thought to trace hot dust just beyond the sublimation limit at the inner edge of the torus. Measuring the emission size can therefore test the assumptions on which dust-RM methods are based. GRAVITY observations (in the *K* band) provide the first resolved view of the shape and structure of the hot dust emission region whose size and orientation can be compared directly with that of the BLR. With its superior sensitivity compared to previous near-infrared interferometers, GRAVITY also allows for more accurate size measurements for a larger sample of AGN. Consequently, through our Large Programme, we have been able to both image the hot dust structure of individual AGN and measure sizes for the whole sample.

The data set on NGC 1068, the archetypical Type 2 AGN, permitted us for the first time to image and spatially resolve the nuclear hot dust in the sublimation region of an AGN, i.e., the inner edge of the putative torus (GRAVITY Collaboration et al., 2020a). Surprisingly, we found a thin, clumpy, ring-like structure of emission with a radius $r = 0.24$ pc and an inclination $i = 70$ degrees, which we associate with the dust sublimation region (Figure 4 left). The observed morphology is inconsistent with the expected signatures of a geometrically and optically thick torus. Instead, the infrared emission shows a striking resemblance to the 22-GHz maser disc, which suggests they share a common region of origin. The dust structure and photometry are consistent with a simple model of hot dust at $T \sim 1500$ K that is behind $AK \sim 5.5$ mag ($AV \sim 90$ mag) of foreground extinction. This amount of screen extinction could be provided by the dense and turbulent molecular gas distribution observed (for example by ALMA) on scales of 1–10 pc. Radiative transfer modelling of the same dataset was done by Vermot et al. (2021). We note that an alternative interpretation of the geometry is offered by Gámez Rosas et al. (2022), based on a different absolute registration which aligns the 12-μm cool dust continuum of recent MATISSE images with 256-GHz bremsstrahlung from hot ionised gas.

In NGC 3783, the non-zero closure phases allowed us to reconstruct an interferometric image of the dust sublimation region using exactly the same dataset as the one to resolve the BLR. The reconstructed image of the hot dust (see right panel of Figure 4) reveals a faint (5% of the total flux) offset cloud which we interpret as an accreting or outflowing cloud heated by the central AGN.

Even in cases where the hot dust cannot be directly resolved, the interferometric technique allows us to derive at least the size of the emitting region. We now have tantalising results about the size of the hot dust structure in eight AGN, which suggest that the 2.2-μm continuum does not follow the expected size-luminosity relation: continuum reverberation experiments (measuring the time delay between the emission from the accretion disc and the hot dust located at the sublimation radius, i.e., the inner torus rim) find correlated variability between the optical and near-infrared emission with a lag that is consistent with reprocessing. The inferred emission radius scales with luminosity as $R \propto L^{0.5}$, as expected if hot dust

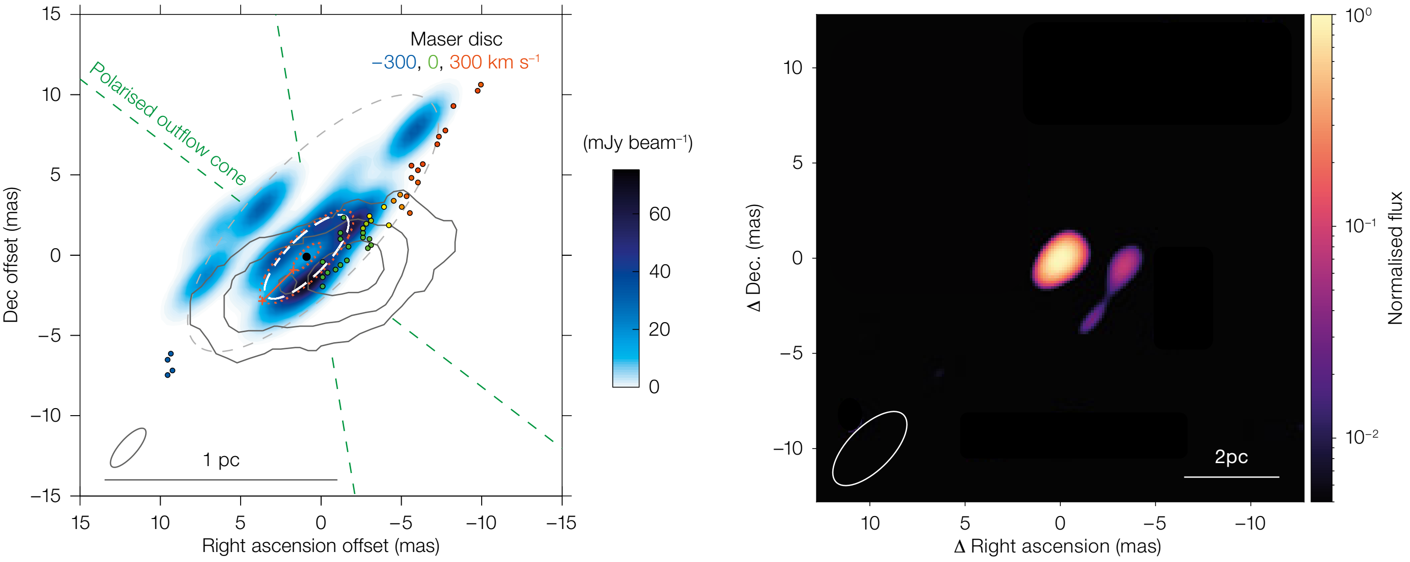


Figure 4. Left: Reconstructed hot dust image of NGC 1068. GRAVITY observes primarily a thin clumpy ring at the expected dust sublimation radius given NGC 1068's AGN luminosity. The bright near side of the ring is cospatial with the megamaser disc, indicating a common origin (GRAVITY Collaboration et al., 2020a). Right: Reconstructed hot dust continuum image of NGC 3783 showcasing the offset cloud 0.6 pc away from the central hot dust at the dust sublimation radius (GRAVITY Collaboration et al., 2021a).

radiation peaks near the dust sublimation radius. The observed normalisation of the relation is smaller than predicted for standard dust composition and grain sizes in the interstellar medium, which may imply the presence of large graphite dust grains near AGN (Kishimoto et al., 2007; GRAVITY collaboration et al., 2020b). Using our robust size measurements, the right panel of Figure 3 shows that the data for the eight AGN yield a rather flatter *R*–*L* relation ($R \propto L^{0.40}$) at slightly over 2σ significance. There are two important conclusions: (i) the scatter amongst the objects seems to be larger than the measurement uncertainties, potentially indicating real physical differences between objects; and (ii) the sizes derived are larger for lower-luminosity AGN, suggesting a systematic effect in terms of dust emissivity or perhaps related to Eddington ratio, or even an inclination bias at high luminosity. At the same time, new results from RM also show that the relation is flatter than previously thought (at about 2σ significance). We have recently been awarded more time on GRAVITY to measure the dust sizes for a further 16 AGN which we will use to fill out our dust *R*–*L* relation. All of these data will allow us to explore possible scenarios for the underlying physical cause of the flattening using state-of-the-art models of dust structures around AGN.

Combined SA and RM and geometric distances

The previous sections illustrate the complementarity of the two techniques — SA and RM — and how SA can be used to test the assumptions of RM. We have now also developed the methods necessary for a combined SA+RM analysis of the BLR structure. The joint analysis provides new opportunities to study the BLR structure, with improved accuracy, in particular of black hole masses. It is also a promising new and direct method by which to measure the geometric distance to AGN. The distances to even nearby AGN are remarkably uncertain: the measured redshift is strongly affected by peculiar motions, but other methods often do not agree. Therefore, distance becomes the dominant source of error in estimating properties such as size, luminosity, and mass. By combining the angular size from SA with the linear size from RM, geometric distances can be derived directly via simple trigonometry. The SA+RM method provides as good a distance measurement for NGC 3783 as other more standard methods such as the Tully-Fisher relation (GRAVITY Collaboration et al., 2021b).

GRAVITY+: the evolution of supermassive black holes and their host galaxies over cosmic time

The examples given above demonstrate the significant progress and enormous potential of GRAVITY in the study of the innermost environment of AGN, including BLR structure and kinematics, 2D velocity-resolved joint analysis of RM and SA, *R*–*L* relations, dust imaging, and improvements to tools and models, to name just a few. While our analysis of the Large Programme data is ongoing[b], the Large Programme has already paved the way for many similar and innovative future studies. The results and experience gained by our team have been instrumental in shaping one of the main science cases (AGN) for GRAVITY+, demonstrating the great potential for future applications (GRAVITY+ collaboration et al., in preparation). A significant upgrade of GRAVITY and the VLTI, GRAVITY+ will boost our understanding in detail of the BLR structure and kinematics over a large range of luminosity and redshifts, thereby overcoming another limitation of RM: a comprehensive study of fast-growing systems at cosmic noon by means of RM is impractical, as the time lag increases both with luminosity (~ $L^{0.5}$) and redshift (~1 + z). High-z luminous quasars have time lags from months to years.

In addition, GRAVITY+ will make significant contributions to other sub-fields of AGN research, including detecting SMBH binaries (Dexter et al., 2020), resolving the dust continuum and emission-line-emitting gas around tidal disruption events, or probing super-Eddington accretion (GRAVITY+ collaboration et al., in preparation).

Acknowledgements

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References

Antonucci, R. R. J. & Miller, J. S. 1985, ApJ, 297, 621
Baskin, A. & Laor, A. 2018, MNRAS, 474, 1970
Dalla Bontà, E. et al. 2020, ApJ, 903, 112
Dexter, J. et al. 2020, ApJ, 905, 33
Gámez Rosas, V. et al. 2022, Nature, 602, 403
GRAVITY Collaboration et al. 2018, Nature, 563, 657
GRAVITY Collaboration et al. 2020a, A&A, 643, A154
GRAVITY Collaboration et al. 2020b, A&A, 634, A1
GRAVITY Collaboration et al. 2020c, A&A, 635, A92
GRAVITY Collaboration et al. 2021a, A&A, 648, A117
GRAVITY Collaboration et al. 2021b, A&A, 654, A85
Kaspi, S. et al. 2000, ApJ, 533, 631
Kishimoto, M. et al. 2007, A&A, 476, 713
López-Gonzaga, N. et al. 2016, A&A, 591, A47
Vermot, P. et al. 2021, A&A, 652, A65
Wang, J.-M. et al. 2017, NatAs, 1, 775

Notes

[a] Improved data reduction methods and recipes resulting from this Large Programme have already been incorporated into the official GRAVITY pipeline, or are in preparation for this in the context of the GRAVITY+ upgrade.

[b] We plan to release processed data within two years of the completion of the observations (i.e., by the end of 2023). We will make available via the ESO Science Archive Facility our reduced and calibrated (fringe-tracker) visibilities and spectra, time-averaged phase data, and reconstructed continuum images.

Zdenek Bardon/ESO

This picture, taken from ESO's La Silla Observatory in Chile, shows bright red streaks known as red sprites. These are an elusive form of lightning that occurs well-above storm clouds, discharging electricity high up in Earth's atmosphere at an altitude of 50–90 km. In addition to occurring much higher in the sky than regular lightning, they are cooler than the white lightning we usually see and appear much fainter. Red sprites are very difficult to catch: the first photographic evidence for them was only taken in 1989.

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HD 74438: a Young Spectroscopic Quadruple as a Possible Progenitor of Supernovae Ia

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Type Ia supernovae (SN Ia) are amongst the most energetic events in the Universe. They are used as standard candles to measure cosmological distances and they produce a rich nucleosynthesis; they are fundamental objects to understand the chemical evolution of galaxies. It is thought that SN Ia are produced by processes occurring in tight binaries including at least one carbon–oxygen white dwarf (WD). Such binaries could emerge from the dynamical evolution of high-multiplicity stellar systems such as the young spectroscopic quadruple HD 74438, recently detected in the Gaia–ESO Survey. Follow-up spectroscopic observations in South Africa and New Zealand, as well as the use of archival ESO spectra, allow us to characterise its orbital and astrophysical parameters. Modelling the dynamical evolution of stellar quadruples shows that such systems can produce WD mergers, possible progenitors of SN Ia.

Can we neglect stellar quadruples?

Amongst low-mass stars, quadruple systems represent only 1–5% of all systems (see, for example, Tokovinin, 2014; Reylé et al., 2021) while being, with triples, the dominant multiplicity amongst the most massive stars (Moe & Di Stefano, 2017) — leaving only a few percent of single stars. The shape and structure of a multiple system become relevant starting with quadruples, since triples are stable only in a configuration of a binary orbited by a distant companion, i.e., a 2+1 configuration. In quadruples, two architectures can be observed, although not with the same degree of stability: the 1+1+2 = 1+3 configuration and the 2+2 configuration, i.e., two short-period binaries gravitationally bound on a longer period. The 1+3 configuration is strongly bound and harbours 3 hierarchies while the 2+2 configuration is considered as weakly bound and harbours only 2 hierarchies: two inner short periods and one outer longer period. Statistically, more than 2/3 of quadruple systems are observed with the 2+2 configuration (Tokovinin, 2018), but it is not clear whether this comes from observational biases or whether there are physical grounds for such a situation.

Stellar multiplicity in the Gaia–ESO Survey

The Gaia–ESO Survey (GES; Gilmore et al., 2012; Randich et al., 2013) is one of the first large spectroscopic surveys with medium to high resolution designed to complement the Gaia mission as regards spectroscopy, given that the Gaia RVS spectrograph is limited to $G \sim 14$ and has a resolution of only 11 500. The GES was not optimised to detect stellar multiplicity, but Working Group 14, a specific working group aiming at detecting outliers, has focused on the detection of spectroscopic binaries (SB) with one or more visible components (SB1, SB2, SB3 and SB4) through radial velocity (RV) variations. Within the previous releases it was already possible to identify about 800 SB1 (Merle et al., 2020), 340 SB2, 10 SB3 and even one SB4 (Merle et al., 2017), most of them being new detections. The last release will increase the number of SB2 and SB3 detected thanks to the design of new templates for cross-correlating spectra (Van der Swaelmen et al., in preparation). After correcting for detection efficiency, we obtain an SB1 fraction of 10±2% and an SB2 fraction of about 2%, yielding a total GES SB fraction of 12%, well in line with the estimate of the close binary fraction of 15±3% by Moe & Di Stefano (2017) for solar-type stars.

The unique SB4 from the GES

HD 74438 is a bright target ($G = 7.5$) which shows four components in its GES spectrum, making this target the unique SB with 4 visible components (SB4) as revealed by the GES cross-correlation functions (CCF). From the preliminary analysis of the 46 GES epochs, we already suspected it to be a bright SB2 (components A and B) evolving around another dim SB2 (components C and D): i.e., an SB4 in a 2+2 configuration. Interestingly, this quadruple belongs to a young and close-by open cluster in the Vela constellation, and indeed the RVs of the pairs bracket the mean RV of the cluster. It was suspected to be a stellar triple by dint of lying 0.9 mag above the main sequence of the cluster (Platais et al., 2007). All the spectra within the GES were taken on the same night, 18 February 2014, within a period of 2.5 h. It was already possible to set upper limits to the inner periods, but monitoring this SB4 rapidly became mandatory. To be detected as an SB4, the outer period of the quadruple system cannot exceed a few years. This limitation makes spectroscopic quadruples very rare objects. Before the discovery of the SB4 nature of HD74438, fewer than 10 SB4 were known, most of them also being eclipsing binaries. In less than three years, we obtained sufficient follow-up observations with the High Resolution Spectrograph at the Southern African Large Telescope (HRS/SALT) and the HERCULES spectrograph at the University of Canterbury Mount-John Observatory (HERCULES/UCMJO) in New Zealand. Combined with archival ESO data from GIRAFFE spectra taken in 2004, it was possible to constrain the outer orbit.

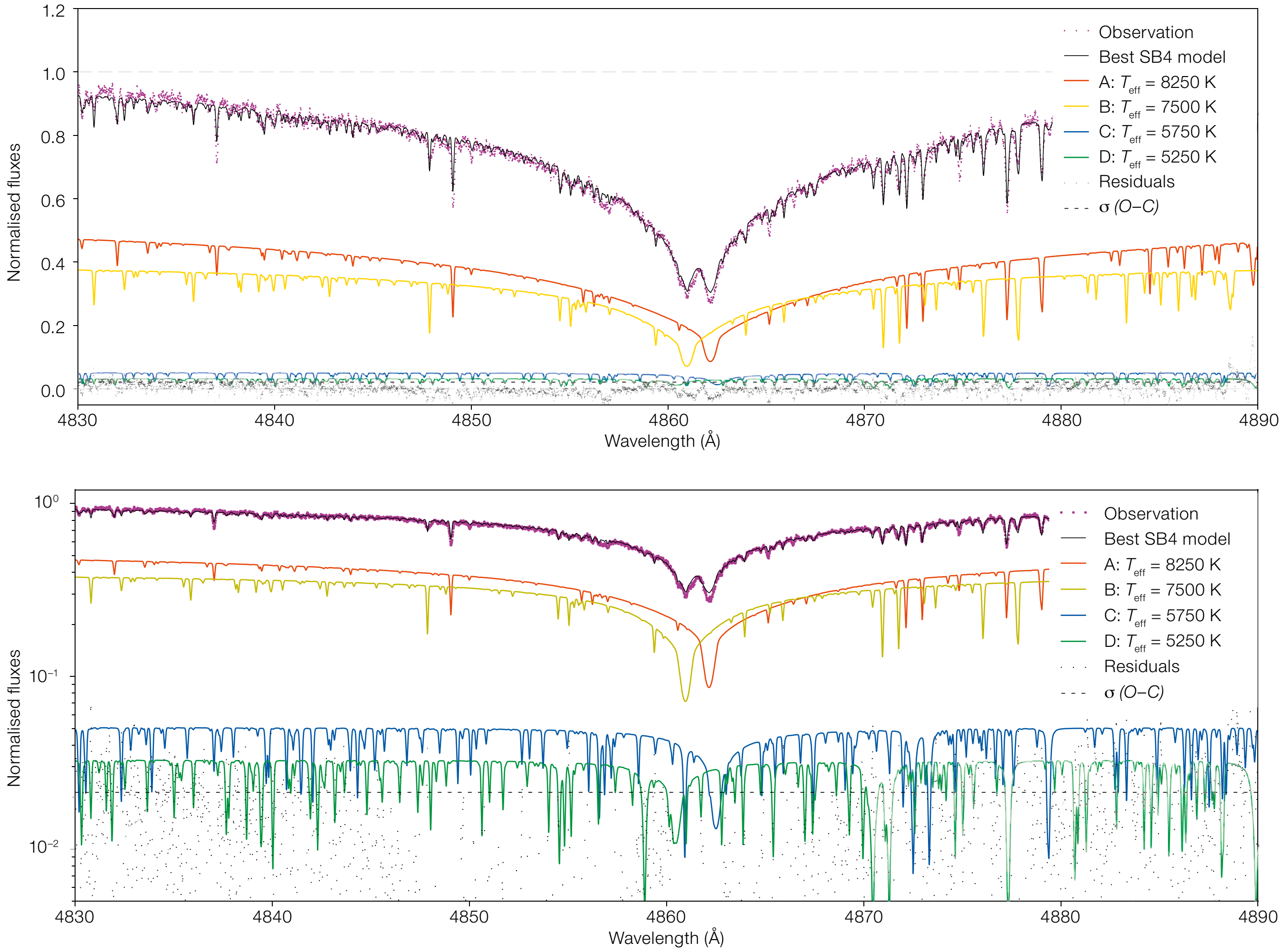

Figure 1. Spectral fitting of the UVES/GES observed composite spectrum (magenta dots) taken on JD 2 456 707.120 (2014.134) around Hβ with a S/N = 104. The best-fit SB4 composite model is shown in black. The individual spectra are also shown and colour-coded as given in the legend; they give an idea of the contribution of each component to the total flux. Normalised fluxes are represented on a linear scale (top) and a logarithmic one (bottom).

A tight quadruple with non-coplanar orbits?

Astrophysical parameters

An age of 43 Myr and a solar metallicity for the cluster IC2391 (Randich et al., 2018; Spina et al., 2017) indicate that the four components are still on the main sequence. From a grid of composite spectra, we fitted two HRS/SALT spectra (having a spectral resolution of 65 000) where the four components were well separated (see Figure 1 of Merle et al., 2022). For illustrative purposes, and using the derived effective temperatures, we compare in Figure 1 the observed Ultraviolet and Visual Echelle Spectrograph (UVES) spectrum (spectral resolution of 47 000) with a S/N > 100 taken at JD 2 456 707.120 (2014.134) with a synthetic composite spectrum computed using Kurucz atmosphere models[1] and the 1D LTE radiative transfer code Turbospectrum[2]. The individual spectra are combined, taking account of the RV and luminosity of each component. The residuals (grey dots) and their dispersion (black dotted horizontal lines) are shown; looking at the logarithmic version (bottom panel) we can see that the flux contribution of the weakest component, D, is higher than the 1% contribution of the noise and the 2% dispersion of the residuals, giving credence to the derived temperatures. Using Gaia DR2 parallaxes and photometry, it was possible to derive the individual luminosities that sum up to 15.7 ± 1.8 $L_\odot$, in excellent agreement with the luminosity computed in Gaia DR2 by Andrae et al. (2018). Interestingly, it means that in the optical it is therefore possible to detect components almost 20 times less luminous than the brightest one (luminosity ratio of 18.5). In addition, spectroscopic and dynamical masses are derived and are in good agreement, with a total mass of about 5.3 ± 0.1 $M_\odot$, much larger than the 3 $M_\odot$ inferred from the integrated spectral type (A2V).

Orbital parameters

Thanks to the high spectral resolution monitoring carried out with SALT in South Africa and HERCULES in New Zealand, and completed with the archival ESO GIRAFFE spectra, it was possible to derive the orbital parameters of the three

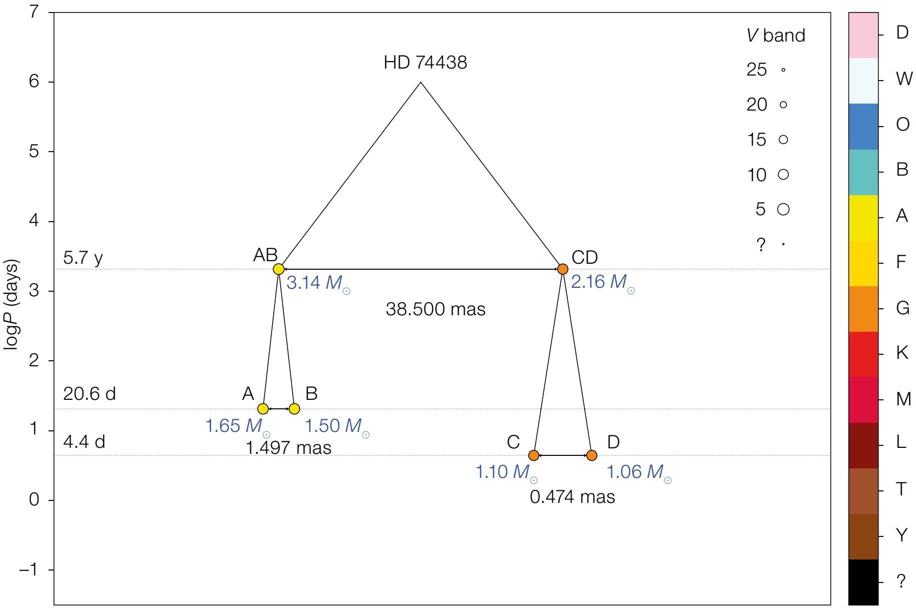

Figure 2. Mobile diagram of the 2+2 spectroscopic quadruple stellar system HD 74438. A G-type binary of 4 days is orbiting an A-type binary of 21 days in almost 6 years. The total mass of the system is 5.3 ± 0.1 $M_\odot$. Simulations show that such quadruples could undergo secular evolution leading to three merger events.

orbits (i.e., radial velocity amplitudes, orbital periods, eccentricities, periastron arguments and times, and the center-of-mass RV of 14.5 ± 0.2 km s^{-1} — in excellent agreement with the parent cluster RV from Bravi et al., 2018). Inclinations and semi-major axes are also deduced. The resulting global architecture of HD 74438 is presented in Figure 2. It was also possible to constrain the orientation of the outer orbit on the sky, using astrometric data from Tycho-1 and 2, and the mean proper motions (relative to the parent cluster) of Gaia DR2 and eDR3, and to remove the degeneracy on the ascending node and the inclination on the sky (see the methods described in Merle et al., 2022). Nevertheless, the ascending nodes of inner orbits are not reachable with Gaia data and would require specific interferometric observations with, for example, the Precision Integrated-Optics Near-infrared Imaging Experiment (PIONIER). The inclinations on the sky alone cannot allow one to decide whether the inner orbits are coplanar or not.

Secular evolution at work?

Indirect evidence

Despite the missing arguments of the ascending nodes of the inner orbits, indirect evidence favours non-coplanar inner orbits. Indeed, when the eccentricity of the C–D pair is compared to the eccentricities of other SB2 from the SB9 catalogue (Pourbaix et al., 2004) and eclipsing binaries (Zasche et al., 2019) with similar G spectral types and similar periods, it appears that they are all circularised. According to Geller, Hurley and Mathieu (2013), binaries with orbital periods lower than 7–8 days should already have been circularised, given the age of the parent cluster. This observational fact points toward the existence of a dynamical influence of the A–B pair on the C–D pair. In triple systems (1+2 configuration), such a dynamical effect of the distant star on the inner binary is produced by exchange of angular momentum between the inner binary and the outer orbit on a secular timescale, i.e., timescales larger than the orbital periods. This effect is called von Zeipel-Lidov-Kozai (ZLK) oscillations. The only condition for a such secular evolution to operate in triple systems is that the initial mutual inclination should be in the range 40° to 140°.

Future evolution of HD 74438

In quadruples, such dynamical effects can lead to even more complex evolution because a double effect can occur between any of the two inner binaries and the outer orbit. The restricted inclination range required in triple systems to pump up the inner eccentricities no longer applies in quadruple systems. We simulated the future evolution of HD 74438 using the state-of-the art Multiple Star Evolution code (Hamers et al., 2021) that includes gravitational dynamics with direct N-body integration and secular evolution, stellar evolution effects, and binary and triples interactions in eccentric orbits (such as mass/angular momentum transfer and common envelope evolution). The trajectories of one of these future evolutions are shown in Figure 3. Simulations based on the orbital parameters and their uncertainties show that in half of the cases, at least one merger event occurs. In a quarter of cases, inner binaries will merge, producing a double WD that also will ultimately merge leaving a WD with a sub-Chandrasekhar mass. Simulations of future evolutions of HD 74438 show that tight quadruple stellar systems offer a possible new way to form SN Ia.

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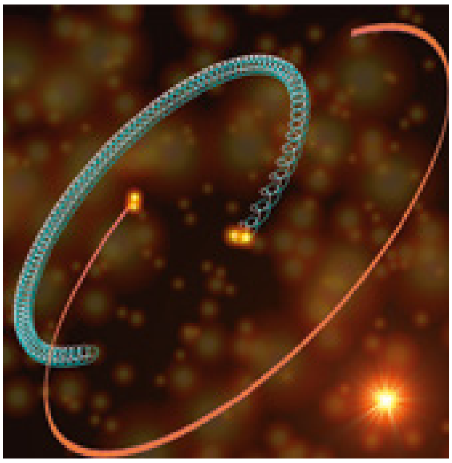

Figure 3. One simulation of the trajectories of the quadruple stellar system HD 74438: the two close pairs, having orbital periods of 21 and 4 days, orbit around their centre of mass in six years. At some point, the two pairs could merge into white dwarfs giving rise to a thermonuclear supernova, as illustrated in the bottom right.

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References

Andrae, R. et al. 2018, A&A, 616, A8
Bravi, L. et al. 2018, A&A, 615, A37
Geller, A. M., Hurley, J. R. & Mathieu, R. D. 2013, AJ, 145, 8
Gilmore, G. et al. 2012, The Messenger, 147, 25
Hamers, A. S. et al. 2021, MNRAS, 502, 4479
Merle, T. et al. 2017, A&A, 608, A95
Merle, T. et al. 2020, A&A, 635, A155
Merle, T. et al. 2022, Nature Astronomy, 6, 681
Moe, M. & Di Stefano, R. 2017, ApJS, 230, 15
Platais, I. et al. 2007, A&A, 461, 509
Pourbaix, D. et al. 2004, A&A, 424, 727
Randich, S. et al. 2013, The Messenger, 154, 47
Randich, S. et al. 2018, A&A, 612, A99
Reylé, C. et al. 2021, A&A, 650, A201
Spina, L. et al. 2017, A&A, 601, A70
Tokovinin, A. 2014, AJ, 147, 87
Tokovinin, A. 2018, ApJS, 235, 6
Zasche, P. et al. 2019, A&A, 630, A128

Links

[1] Kurucz atmosphere models: http://kurucz.harvard.edu/grids.html, the ap00k2.dat in the GRIDP00 directory
[2] Turbospectrum code: http://ascl.net/1205.004
[3] GAIA website: https://www.cosmos.esa.int/web/gaia
[4] DPAC website: https://www.cosmos.esa.int/web/gaia/dpac/consortium
[5] Vizier website: https://vizier.cds.unistra.fr/

The beautiful edge-on spiral galaxy NGC 3190 with tightly wound arms and a warped shape that makes it resemble a gigantic potato crisp, as seen by ESO’s Very Large Telescope. Supernova SN 2002bo is found in between the ‘V’ of the dust lanes in the south-western part of NGC 3190. SN 2002cv is obscured by a large amount of dust and is therefore not visible. This colour composite is based on images obtained with FORS1 on UT2 (Kueyen) in four filters (*B*, *V*, *R* and *I*). The observations were done in the framework of a programme aiming at studying the physics of Type Ia supernovae. The field of view is 6.15 × 5 arcminutes. North is up and East is to the left.

Telescopes and Instrumentation

A powerful laser beam is launched from the VLT´s 8.2-metre Yepun Telescope and excites sodium atoms high in the Earth´s mesosphere, creating an artificial star at 90 km altitude. This laser guide star was part of the VLT's Adaptive Optics Facility and is nowadays complemented by a more powerful 4 Laser Guide Star Facility, which allows astronomers to correct images and spectra for the blurring effect of the atmosphere. Across the upper part of the image is the Milky Way, our own galaxy, seen in the sky perfectly edge-on. The yellowish core crossed by prominent dark lanes is the central part of our home galaxy. The dark lanes are huge clouds of interstellar dust, opaque to visible light. The ancient Andean civilizations saw in these dark nebulae their constellations, with the shapes of common animals, such as the lama, here visible on the right.

G. Hüdepohl/ESO (www.atacamaphoto.com)

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Overview of the Additional Representative Images for Legacy (ARI-L) Development Project for the ALMA Science Archive

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The Additional Representative Images for Legacy (ARI-L) project is a European Development project for ALMA Upgrade approved by the Joint ALMA Observatory and ESO in 2019. It aims to increase the legacy value of the ALMA Science Archive by bringing the reduction level of ALMA data from Cycles 2 to 4 close to that of data from more recent cycles processed for imaging with the ALMA Pipeline. To date, ARI-L has produced, assessed the quality of, and delivered more than 150 000 images. These represent more than 85% of the science datasets from Cycles 2 to 4 processable with the ALMA Pipeline but lacking pipeline-generated images, and accordingly the project accomplished all its goals during its official runtime.

ARI-L project rationale

ALMA was the first radio astronomy facility to offer calibrated, deconvolved images and data cubes as fundamental data products of the Joint ALMA Observatory (JAO).

These data products are not unique because of the relatively large freedom in parameter choices during the interferometric imaging process, but even in their generic form they provide a quick way for users to assess the data quality, the content of the data products and the interesting spatial and spectral regions. Depending on the science case, the pipeline-generated data products may also be used for scientific analysis. For these reasons, the image products are delivered to ALMA users through the ALMA Science Archive (ASA).

From ALMA's Early Science period up to Cycle 3 (i.e., up to projects observed in late 2015), the part of the ALMA pipeline dedicated to imaging was not available. The staff at the observatory and at the ALMA Regional Centres (ARCs) manually performed the quality assurance (QA2) of the data before they were delivered to the principal investigators (Petry et al., 2020). This manual procedure was carried out for over 1800 ALMA projects. The manual imaging of each full data set is very time consuming, so the analysis often focused on only a small subset of a project's calibrated data that was just large enough to assess the quality, mostly for the defined purposes of the project proposers rather than for potentially broader goals of users of the archival data. As a result, only a very small fraction of all raw data (< 10%) was converted into images and image cubes, and typically they do not include images of the calibrators. This fraction increased dramatically from Cycle 5 (i.e., from 2017) when the ALMA Science Pipeline was used almost exclusively for QA2 data reduction.

The availability of deconvolved images and data cubes vastly speeds up researchers' data analysis process. Archive researchers can not only download the images for local analysis, but also use the ALMA archive remote visualisation tools.

The use of a well-established pipeline makes the data analysis process more efficient and the products more homogeneous, even across projects, arrays and epochs, so the products can be compared or combined accurately. This aids investigation of variability, spectral and/or spatial behaviour, or the use of statistical techniques on samples taken from multiple observations.

The main goal of the ARI-L project was to use the ALMA Imaging Pipeline (as introduced in 2017) on the data from early observing Cycles (2–4) to create, where

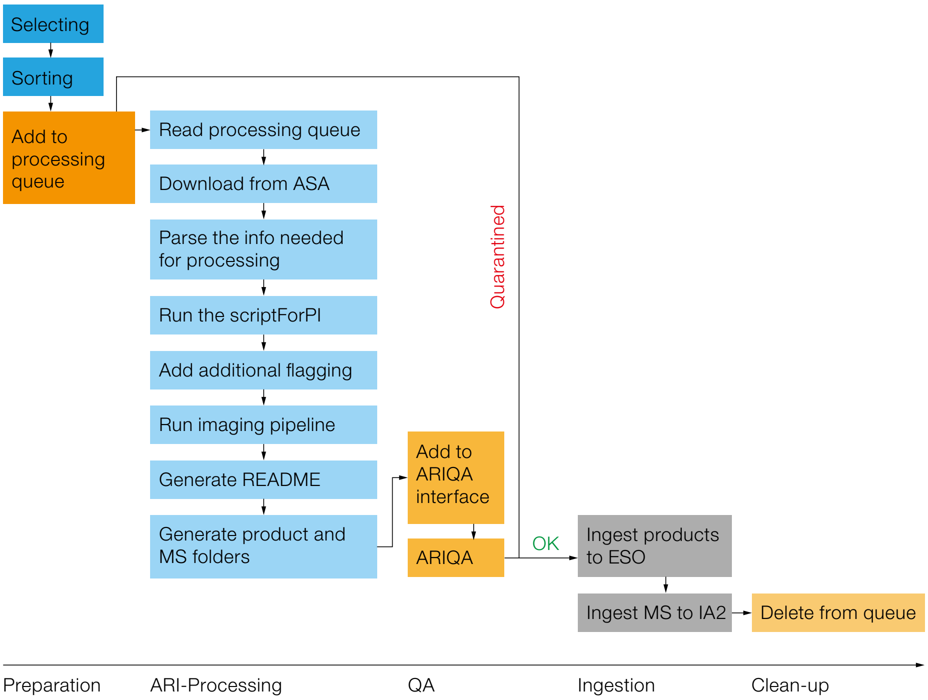


Figure 1. The decision tree and the different processes of the ARI-L project as applied to each MOUS in Cycles 2–4.

	Cycle 2	Cycle 3	Cycle 4	Total
Processable MOUS	973	1603	605	3181
Delivered	701	1495	518	2714
Processing and QA issues	272	108	87	46
Delivered fraction (%)	72.5	93.3	85.6	85.3

Table 1. Numbers and properties of datasets, grouped, as in the ASA, in Member Observing Unit Sets (MOUS) for ALMA Cycles 2–4 processed in the ARI-L project. Statistics are also reported for MOUS that failed the quality assurance procedure, either because of issues in the processing or identified in the QA stage. Fraction of successfully delivered MOUS are also reported. For comparison, the ARI-L main goal was to reach the 70% of the processable MOUS with a best effort goal of 80%.

possible, data products of the same completeness and quality as ALMA is now creating for new observations and to ingest them into the ASA.

This objective required the production of a uniform set of full data cubes and continuum images, covering at least 70% of the data from Cycles 2–4 which can be processed with the ALMA Pipeline, with a best efforts goal of 80%.

The project began processing in June 2019 and its first products were ingested into the ASA in November 2019. After the three years of its official runtime (and despite operating under pandemic conditions) the ARI-L project delivered more than 85% of the data from Cycles 2–4 that can be processed with the ALMA Pipeline, reaching and surpassing all its goals.

The ARI-L cubes and images complement the much more limited number of archival image products generated during the data quality assurance stages (QA2), which cover only a small fraction of the available data for those cycles.

The ARI-L project workflow

When requesting observations, investigators specify their observational requirements as a series of science goals. In terms of observational operations, these correspond to one or more “Group Observing Unit Sets”, each of which may be split into various “Member Observing Unit Sets” (MOUS) that include the instrumental settings needed to reach the investigator’s goals. MOUS constitute the selection and analysis level for ARI-L datasets.

To be selected for processing by ARI-L, MOUS must be accessible for public download, with calibration scripts available in the ASA. They must have been observed in modes that could be handled by the imaging tasks of the ALMA Pipeline at the time of the project definition (i.e., excluding solar, full-Stokes, very-long-baseline interferometry, and total power observations).

The ARI-L project uses the Imaging Pipeline outside the range of goals for which it has been commissioned, as it is the best tool currently available to create homogeneous images of data from past cycles.

The ARI-L products are generated by a Python-based workflow engine. For each processable MOUS this starts by downloading from the ASA the data packages (including raw data and calibration scripts and tables and existing products). The workflow then restores the calibration, generates the data products with the Imaging dedicated part of the ALMA Pipeline, extending the processing to include datacubes for observations of calibrators. Finally, the ARI-L image products and calibrated measurement sets are packaged for permanent storage.

All ARI-L images are primary-beam corrected. The corrected images cover a region of diameter equal to the full width half maximum (FWHM) sensitivity of the primary beam centred at the pointing position. The approximate geometric

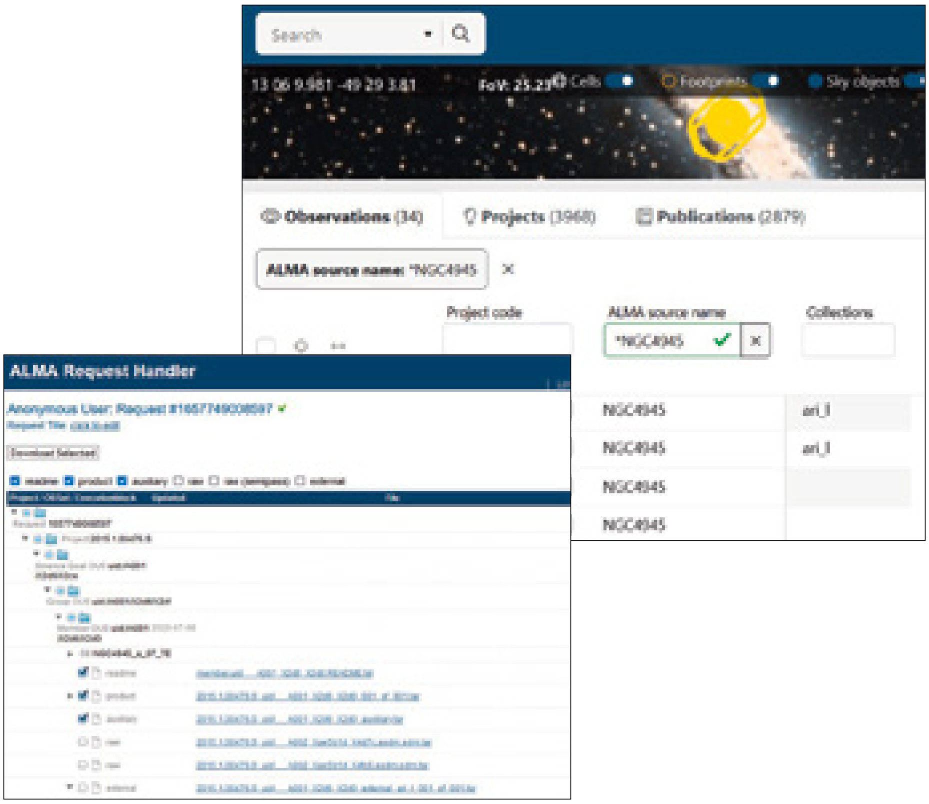
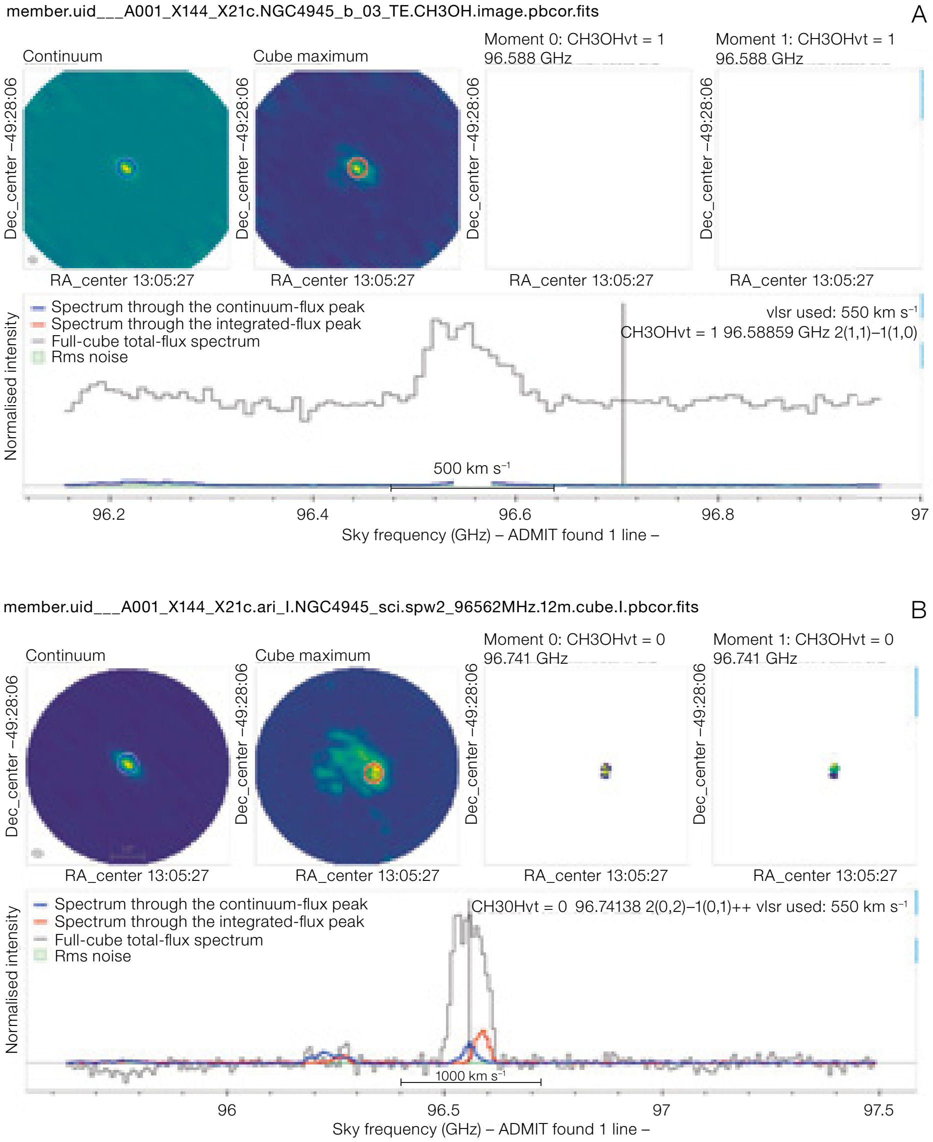


Figure 2. Snapshots of the ASA query interface showing (top) a search for projects in Cycle 4 (i.e., project code 2016*), with the “ari_l” flags in the “Collections” column, and (bottom) the download interface listing the ARI-L products as “External”. Note that single ARI-L images can be accessed with the remote CARTA viewer available for all the ASA images.

Figure 3. Snapshots of the ASA query interface showing the interactive previews for an MOUS in the project 2015.1.01151.S comparing the CH3OH line in the galaxy NGC 4945 in the QA2 image (panel A) and in the ARI-L image (panel B) and for the CN line in NGC 1068 in the QA2 image (panel C, following page) and in the ARI-L image (panel D, following page).



centre is usually used for mosaics, out to the FWHM of the most distant fields. The Imaging Pipeline by default attempts automasking of the images. Primary-beam and mask maps are delivered together with the product image. For cubes, the channel resolution is defined by the native resolution of the observations but also takes into account that the nominal channel size has been reduced by a factor of two by Hanning smoothing. The Briggs robust parameter is set to 0.5 for all data unless the Imaging Pipeline indicates a different approach.

The ARI-L imaging products undergo a quality assurance step before they are delivered to ESO and then to the JAO for ingestion into the ASA. A README file is enclosed in the ARI-L product folder; its purpose is to trace the history and hierarchy of the dataset used to generate all the product images.

For all the successfully processed MOUS that pass quality control, the final ARI-L calibrated measurement sets are stored in a dedicated storage system outside the ASA that is hosted and maintained by the INAF-IA2[1] facility. The calibrated sets are available to the user community via the ARI-L webpage[2].

A visual representation of the project workflow is shown in Figure 1. Further details of the ARI-L processing and quality procedures are described by Massardi et al. (2021).

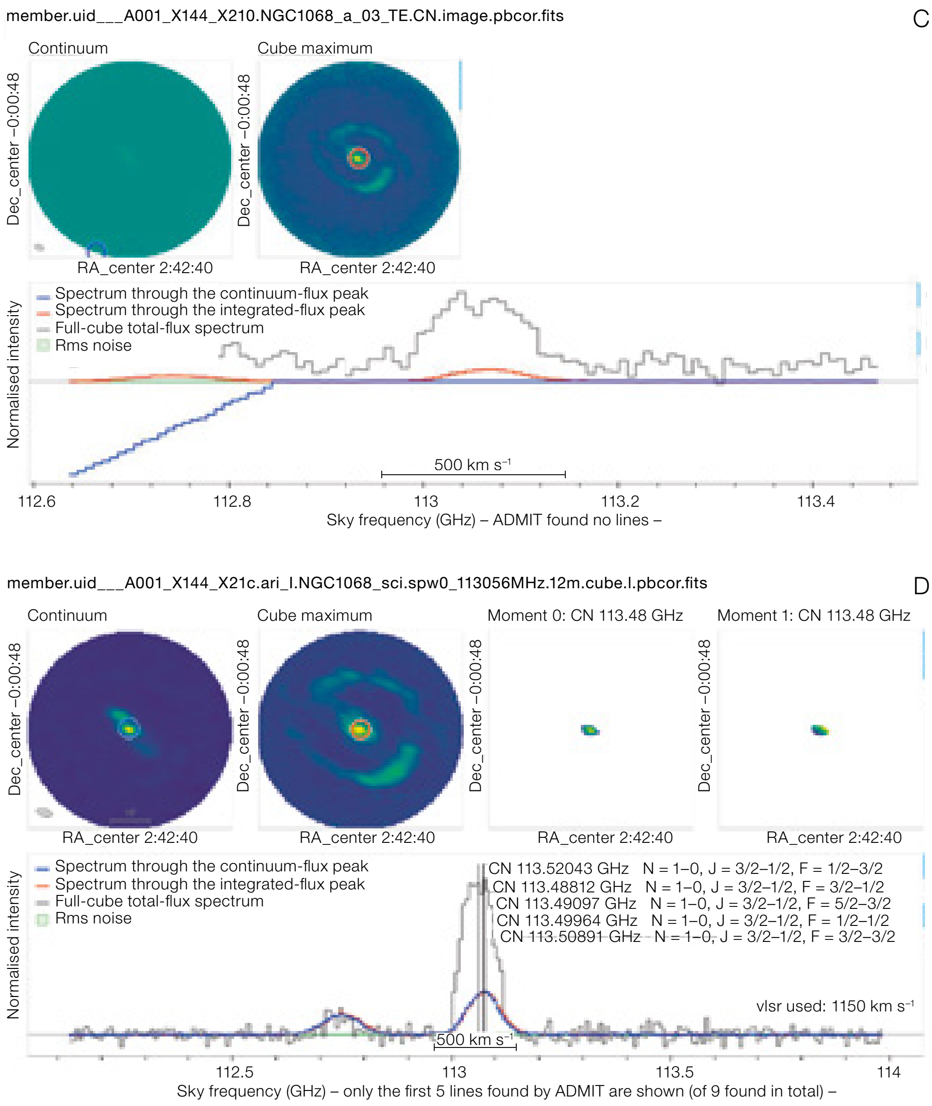
ARI-L successes

Table 1 summarises the statistics of MOUS processed in the ARI-L project. ARI-L products are currently available for 2714 MOUS stored in the ASA. They amount to more than 410 000 files (including images, masks, readme files). 150 247 of the ARI-L archived files are continuum and cube images, of which 84 626 are for science targets and 65 621 are for calibrators. The total number of channels for which there is an ARI-L map in the ASA is 126 707 258.

Images underwent a quality control before being delivered to ASA. Outcomes and logs of the calibration and imaging processing were verified, and completeness and sensitivity and resolution achievement of the imaging products certified. When a failure was encountered, causes were investigated, and, when available, reprocessing solutions were applied to attempt recovery. Only when reprocessing required changes in the calibration scripts available from the archive, or the pipeline application was not suitable for processing, was the MOUS quarantined. An extension of six months has been allocated to the project, starting in June 2022, to continue the effort on such unfortunate instances.

So far 703 331 ARI-L files have been downloaded, meaning that on average each ARI-L file has been downloaded 1.7 times.

Sources belonging to MOUS that have been successfully imaged by ARI-L are flagged “ari_l” in the “Collections” column of the ASA query interface (see Figure 2). It is therefore possible to apply filters to queries. Once a line is, or lines are, selected for download, ARI-L products can be accessed and downloaded as “External products”.



A total of 24 793 preview files of ARI-L fits images/cubes have been looked at in the ASA interface. The ARI-L images made possible the inclusion of a preview in the archive for hundreds of MOUS for which the limited spectral coverage of the QA2 images did not allow it. In particular, ARI-L delivered images of the calibrators — mostly radio loud quasars, local active galactic nucleus cores or supernova remnants — for each of the delivered MOUS; in usual QA2 processing images of the calibrators are not produced.

The use of ALMA data elaborated by ARI-L data should be acknowledged using the standard ALMA acknowledgement statement and it is suggested, and would be appreciated, that Massardi et al. (2021) be cited when ARI-L data are used (see, for example, Di Mascolo et al., 2021; Pantoni et al., 2021; and Van't Hoff et al., 2022).

The ASA legacy enhancement with ARI-L products

ARI-L imaging products are highly relevant for many science cases and significantly enhance the possibilities for exploiting archival data.

Use of the archive has increased over the years, and the ASA is now considered an important, widely-used resource; currently about 28% of all ALMA publications are either based purely on archival data or use archival data in addition to PI data (Stoehr et al., 2022).

ARI-L products facilitate archive access and data usage for science purposes even for non-expert data miners. They provide a homogeneous view of all data for better dataset comparisons and download selections, make the archive more accessible to visualisation and analysis tools, and enable the generation of preview images and plots similar to those possible for subsequent cycles. Furthermore, archive exploitation is valuable for researchers in countries which are not (yet) ALMA partners. This is especially useful for less well-off countries where computing facilities are more restricted. Archive data are also in demand for teaching as they constitute an excellent testbench for data processing and visualisation tools.

Rather than having to download the raw data, identify the Common Astronomy Software Applications (CASA) versions to use, run the calibration or restoration script, and modify and run the imaging script for hours just to determine whether objects or spectral lines have been detected, researchers can use previously-created products to make these types of assessments in a few minutes.

The availability of ARI-L data in the archive allows the visualisation of products using the remote visualisation tool CARTA[3], including the creation of preview images, which can be displayed directly via the ASA query interface. Data products from the ASA are also accessible for automated post-analysis, for example, with the ALMA Data mining ToolkIT (ADMIT[4]; Teuben et al., 2015), or using the Keywords of Astronomical FITS-Images Explorer (KAFE; Burkutean et al., 2018). Figure 3 clearly shows that the completeness of the ARI-L spectral coverage allows the production of more useful previews with better identification of detections and spectral lines. ASA products can also be accessed directly through virtual observatory services that allow for spectral multi-band comparisons, source identifications, and catalogue reconstruction; the ASA offers ALMA data via Table Access Protocol[5], Simple Imaging Protocol[6] and DataLink[7] services.

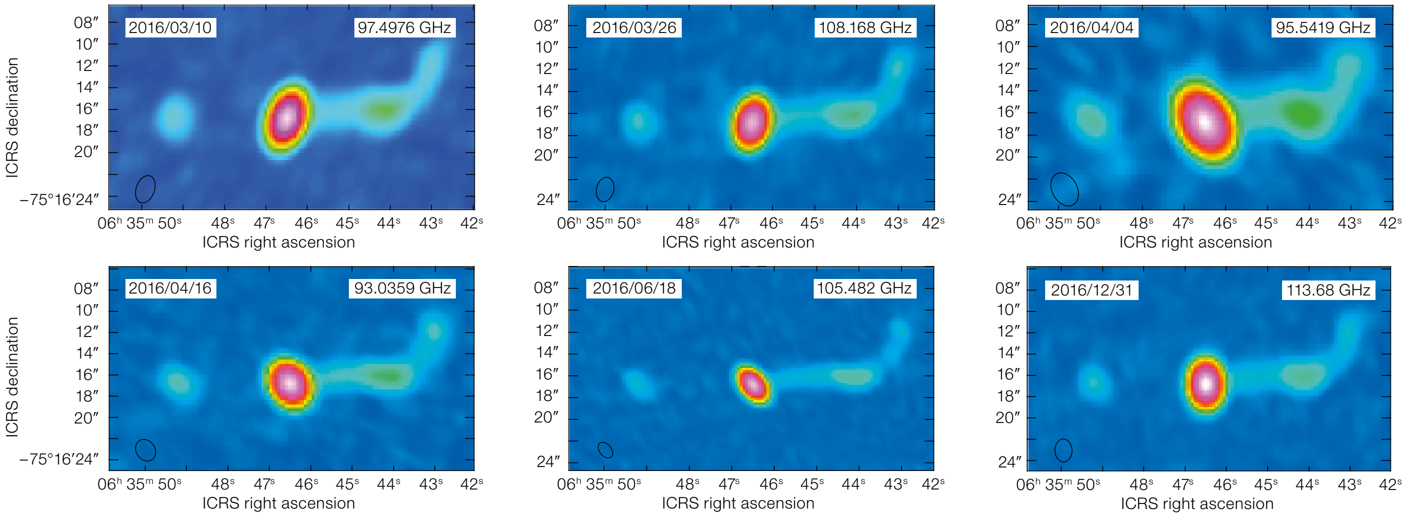


Figure 4. Example of the reconstruction of timelines for calibrator sources. Six epochs of continuum emission are shown, imaged by ARI-L for different archival projects for the calibrator PKS 0635-752. A flare in all the source components is clearly visible in early April, fading over the following months, while a new increase of flux density affects the core component, in December.

ARI-L data strongly enhance the possibilities for comparing archive products in a statistically meaningful way, and for combining archival products, even across different cycles. This is enabled by the enhanced homogeneity given to the products by the use of the imaging pipeline for all of the cycles.

Products can be used to reconstruct timelines to analyse variability (see, for example, Figure 4), to build spectral energy distributions to investigate frequency dependence of emission, or to stack images and statistically enhance signal to noise ratios to obtain average detections. Care is needed to compare products of compatible resolutions and sensitivities, and the scientific significance of initial outcomes may vary from case to case, but they at least provide preliminary insights into what could be reasonably expected (or even improved) with a more detailed analysis of downloaded data.

Finally, the possibility of requesting visibility data sets with the ARI-L calibration applied through the IA2 service makes these measurement sets available without the user's having to install a possibly obsolete CASA version.

Acknowledgements

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References

Burkutean, S. et al. 2018, JATIS, 4, 028001
Di Mascolo, L. et al. 2021, A&A, 650, A153
Massardi, M. et al. 2021, PASP, 133, 085001
Pantoni, L. et al. 2021, MNRAS, 507, 3998
Petry, D. et al. 2020, The Messenger, 181, 16
Stoehr, F. 2022, The Messenger, 187, 25
Teuben, P. et al. 2015, ASP Conf. Ser., 495, 305
Van't Hoff, M. L. R. et al. 2022, ApJ, 924, 5

Links

[1] INAF-IA2 facility: www.ia2.inaf.it
[2] ARI-L webpage: https://almascience.eso.org/alma-data/aril
[3] CARTA visualisation tool: https://cartavis.github.io
[4] ALMA data mining toolkit (ADMIT): http://admit.astro.umd.edu
[5] ASA Table Access Protocol: https://almascience.eso.org/tap/
[6] ASA Simple Imaging Protocol: https://almascience.eso.org/sia2/
[7] ASA DataLink: https://almascience.eso.org/datalink/


ESO/B. Tafreshi (twanight.org)

In this panoramic image the ALMA Observatory's antennas appear to take in the sight of the Milky Way, arching like a galactic rainbow of dust and stars over the Chajnantor Plateau in the Chilean Andes.

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CUBES, the Cassegrain *U*-Band Efficient Spectrograph, aims to bring a unique capability to ESO's Very Large Telescope: an ultraviolet eye on the Universe to complement the Extremely Large Telescope, a super-efficient (> 40%) spectrograph with a spectral coverage of 300–405 nm in the present design and two resolution modes, 20000 and 7000. An option of a fibre link to the Ultraviolet and Visual Echelle Spectrograph is foreseen that will provide the capability of simultaneous optical high-resolution

spectroscopy at $\lambda > 420$ nm. The CUBES design is able to address a treasure trove of scientific cases, from Solar System science to cosmology.

Introduction

Looking to the future of ESO's Very Large Telescope (VLT) there is a long-standing aspiration for an optimised ultraviolet spectrograph (Barbuy et al., 2014; Pasquini, 2014).

ESO's Extremely Large Telescope (ELT), with its 39-metre primary mirror, will be unprecedented in its light-gathering power, but, owing to the choice of protected silver (Ag+Al) for the mirror coatings (excluding M4), its performance drops significantly below 400 nm when compared to bare aluminium. Alternative coatings are under investigation, but in the short–medium term we can assume that the performance of the ELT in the ultraviolet (UV)–blue range will be limited. Indeed, during the Phase A study of the Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology (MOSAIC) instrument (Evans et al., 2016) it was concluded that a blue-optimised instrument on the VLT could potentially be competitive with the ELT at wavelengths shorter than 400 nm.

Motivated by this, in 2018 we revisited (Evans et al., 2018) the Phase A study undertaken in 2012 of the Cassegrain *U*-band Brazilian-ESO Spectrograph. That study investigated a $R \sim 20\,000$ spectrograph operating at 'ground-based UV' wavelengths (spanning 300–400 nm) to open-up exciting new scientific opportunities compared to the (then) planned instrumentation suite for Paranal Observatory (Barbuy et al., 2014; Bristow et al., 2014).

In January 2020 ESO issued a Call for Proposals for a Phase A study of a UV spectrograph to be installed at a Cassegrain focus of the VLT, with the goals of high-efficiency (> 40%) and intermediate resolving power (~ 20 000) in the ground-based UV domain (305–400 nm requirement, 300–420 nm goal). In May 2020 the Cassegrain *U*-Band Efficient Spectrograph (CUBES) Consortium, led by INAF, was selected to carry out the study.

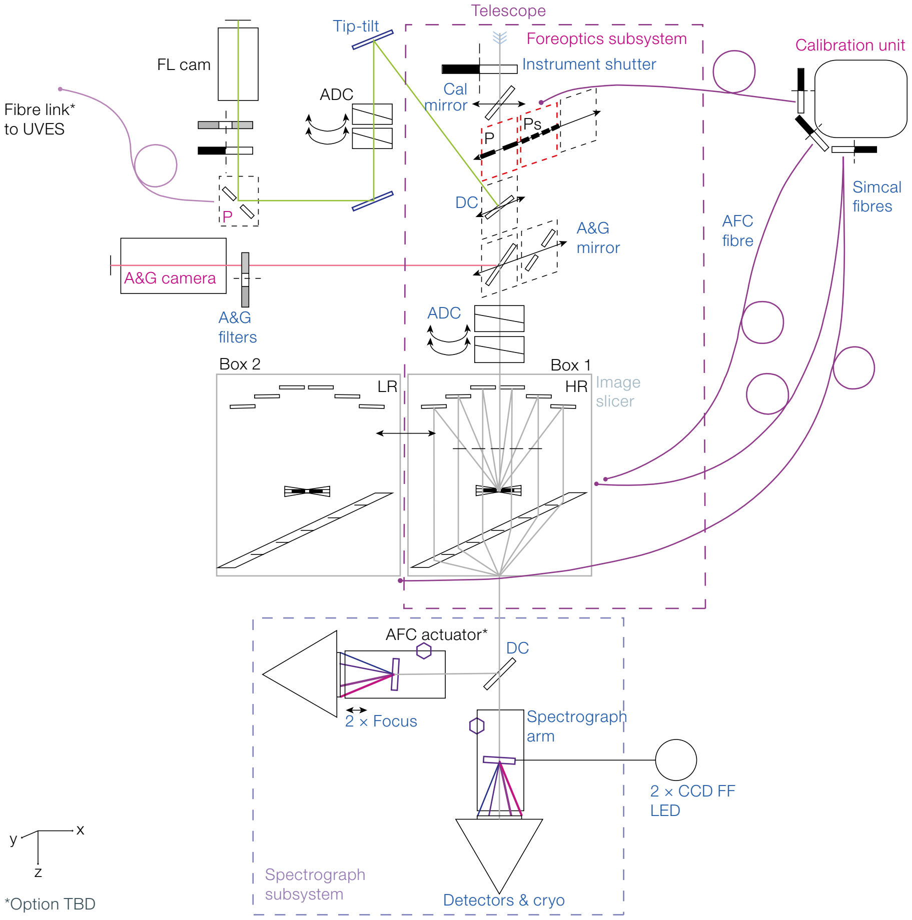


Figure 1. Functional scheme of the CUBES system (in which the light path goes from top to bottom). The following abbreviations are used: DC — dichroic; P — alignment pinhole; Ps — series of pinholes to measure spatial resolution along the slit; AG — acquisition and guiding; AFC — active flexure compensation system; FL — fibre link; ADC — atmospheric dispersion corrector. Optional modules (to be decided in Phase B) are marked with a trefoil sign (Zanutta et al., 2022).

The CUBES project completed its Phase A conceptual design study in June 2021 (Zanutta et al., 2022). After endorsement by the ESO Council at the end of 2021, Phase B started in February 2022 with the signature of the Construction Agreement between ESO and the leading institute of the CUBES Consortium, opening the detailed design and construction phase.

Science cases for CUBES

The CUBES science cases span a broad range of contemporary astrophysics across Solar System, Galactic, and Extra-Galactic science, and are driving the design of the instrument. An overview of CUBES science is given in Evans et al. (2022) and detailed presentations of specific science cases can be found in Opitom et al. (2022: cometary science), Giribaldi & Smiljanic and Smiljanic, da Silva & Giribaldi (2022: Beryllium abundances), Ernandes et al. (2022: nucleosynthesis), Alcalá et al. (2022: accretion and outflows in young stars), Ali & De Propris (2022: stellar populations in galaxies), D'Odorico (2022: the cosmological and galactic missing baryon problems), Balashev & Noterdaeme (2022: molecular hydrogen in absorption at high redshifts).

Instrument concept

The science cases of interest for the CUBES community have been used to identify the Top Level Requirements (TLR) in Phase A and effectively contribute to the design trade-offs, via the use of software tools developed in the study — the exposure time calculator (ETC), and the end-to-end (E2E) simulator (Genoni et al., 2022) — both in Phase A and in the current Phase B. Key TLRs identified for the development of the instrument conceptual architecture and design, were as follows.

- Spectral range: CUBES shall provide a spectrum of the target over the entire wavelength range of 305–400 nm in a single exposure (goal: 300–420 nm).
- Efficiency: The efficiency of the spectrograph, from slit to detector (included), shall be > 40% for 305–360 nm (goal > 45%, with > 50% at 313 nm), and > 37% (goal 40%) between 360 and 400 nm.
- Resolving power (*R*): In any part of the spectrum, *R* shall be > 19 000, with an average value > 20 000, where *R* is defined as the full width at half maximum (FWHM) of unresolved spectral lines of a hollow cathode lamp in the spectral slice.
- Signal-to-noise (S/N) ratio: In a 1-hour exposure the spectrograph shall be able to obtain, for an A0-type star of $U = 17.5$ mag (goal $U \geq 18$ mag), a S/N = 20 at 313 nm for a 0.007 nm wavelength bin. For different wavelength bins, the S/N ratio shall scale accordingly.

An important development in the Phase A study was the potential provision of a second (lower) resolving power (with $R \sim 7000$), to enable background-limited observations of faint sources where spectral resolution is less critical. We have also investigated a potential fibre feed to the Ultraviolet and Visual Echelle Spectrograph (UVES), to provide simultaneous observations at longer wavelengths. This broadens the scientific capabilities of CUBES (by significantly enhancing the cases related to, for example, transients) while also offering operational efficiencies for many cases where observations at longer wavelengths are required to support the UV analysis.

Figure 1 shows the present functional scheme of the CUBES system that envisages the following.

- A calibration unit that provides the light sources necessary to register frames for flat-fielding, wavelength calibration, alignment, the options of simultaneous wavelength calibration and active flexure compensation (AFC) if required.
- A foreoptics (first-stage transfer optics) subsystem that includes an atmospheric dispersion corrector (ADC) and acquisition and guiding functionalities.
- Two image slicers (to enable different spectral resolutions).
- Two arms, both equipped with transmission gratings with a high groove density and working at first order, and cameras. Each arm has its own detector cryostat, which comprises a 9k or 10k CCD as detector, readout electronics, and cryo-vacuum components (both hardware and specific control electronics).
- Instrument control electronics, based on programmable logic controllers complying with the latest ELT electronics standard, to control all the functions in the instrument, excluding the scientific detector system and its associated cryostat and vacuum controller.
- Instrument software comprising control software (based on the ESO's

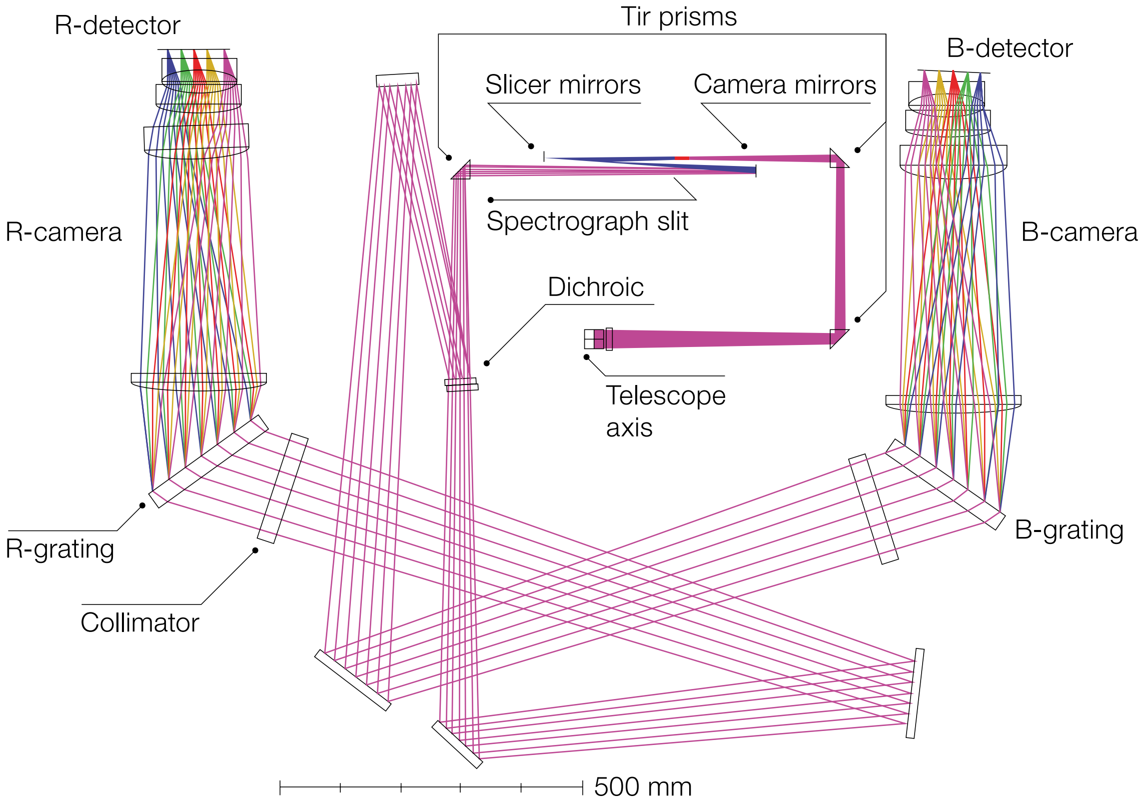


Figure 2. Early optical end-to-end model of the CUBES spectrographs. The light from the foreoptics enters at the prism marked "telescope axis". Note: the four-lens camera shown here has now been replaced by a three-lens camera and a flat CCD window. The tilt of the detector plane is clearly visible.

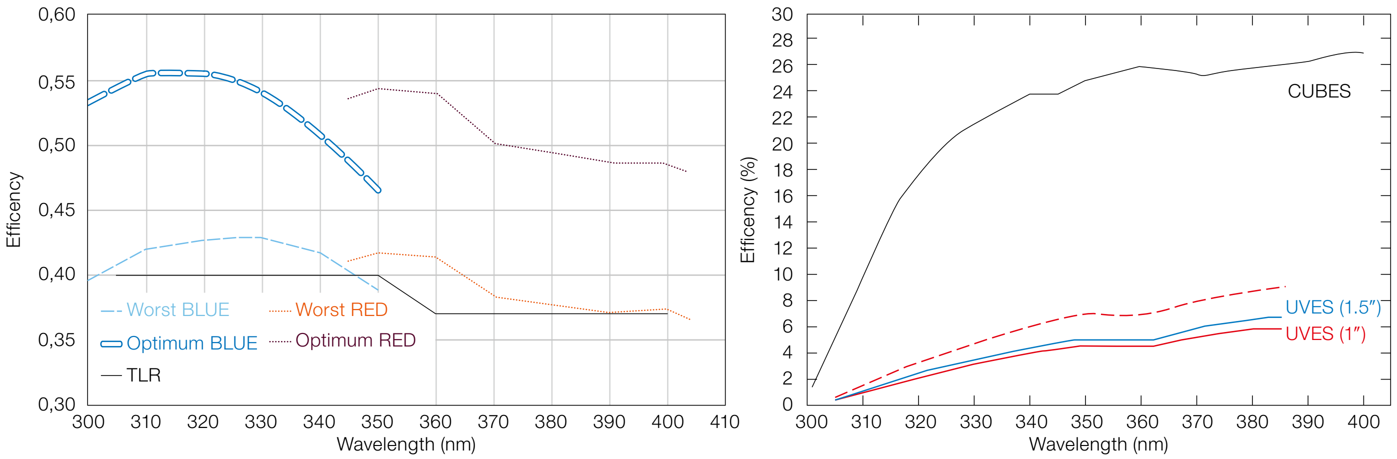


Figure 3. Left: Calculated detective quantum efficiency of the two arms of CUBES (BLUE and RED) for worst and best scenarios. The black line indicates the formal top-level efficiency requirement. The throughput was calculated from the telescope focus, including detector quantum efficiency and slicer vignetting. Right: Comparison of predicted CUBES efficiency (including telescope and atmosphere) with the predicted efficiency in the central wavelengths of the UVES echelle orders, using the ESO Exposure Time Calculator. The dashed red line shows the anticipated gain in performance (a factor of 1.5) resulting from a possible UVES upgrade.

ELT Instrument Control Software Framework), and data-reduction and simulation tools (Calderone et al., 2022).

- A fibre-link unit provides the option of simultaneous observations with UVES (in its red band at 420–1100 nm, via relay optics feeding optical fibres (1 object, 3 sky) subtending a 1-arcsecond aperture and approximately 40 metres long to transmit light from the Cassegrain focus of Unit Telescope 2 to the Nasmyth platform.

Optics

Using two lens doublets and a number of folding prisms (not shown in Figure 1), the foreoptics relays a field of view of 6 × 10 arcseconds at the telescope focus to the entrance plane of the spectrograph. Direct-vision ADC prisms in the parallel beam between the doublets provide atmospheric dispersion correction over the range 300–405 nm for zenith angles of 0–60°. By inserting a dichroic just below the telescope focal plane, light redward of 420 nm may be directed to the UVES fibre feed. During acquisition, the object field is directed by a 45-degree mirror to the acquisition and guiding CCD which is equipped with a set of photometric filters. After acquisition the mirror is moved to pass the centre of the field to the spectrograph.

At the magnified telescope focal plane produced by the foreoptics (scale 0.5 mm arcsec^{-1}), one of two user-selectable reflective image slicers decomposes the rectangular field of view into six slices. Six camera mirrors, one for each slice, re-image the slices on an output slit mask. By using optimised dielectric coatings and careful mask alignment, the slicer efficiency is expected to be > 90% (goal 94%) The output slit mask has six slitlets, corresponding to six slices, each one measuring 0.25 × 10 arcseconds on the sky for the high-resolution slicer (R = 20 000) and 1 × 10 arcseconds for the low-resolution slicer (R = 7000). Further slit mask apertures are illuminated by a ThAr fibre source for simultaneous calibration and/or use by the AFC system.

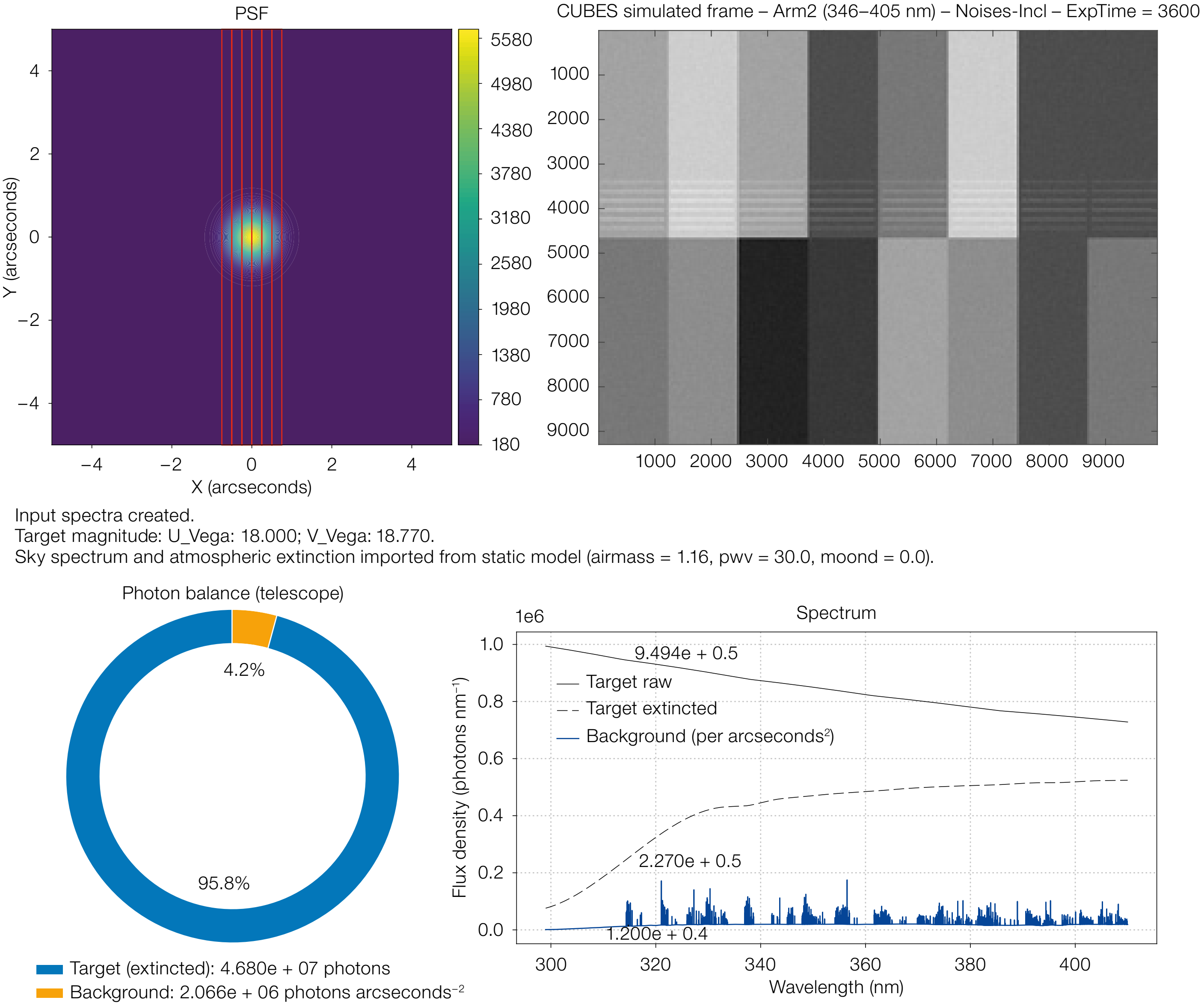
In order to achieve a high (> 20 000) resolution without the efficiency losses associated with crossdispersed echelles, CUBES uses state-of-the-art first-order dispersing elements. Binary transmission gratings produced by electron-beam microlithography and an atomic layer deposition overcoat have been identified as a suitable technology (Zeitner et al., 2022). Their theoretical average diffraction efficiency, based on rigorous coupled-wave analysis, is > 90%. A first prototype, funded by the Fundação de Amparo à Pesquisa do Estado de São Paulo, was produced and tested as early as 2018; further prototyping activity is underway and a test and characterisation report will be presented at the Preliminary Design Review.

As shown in Figure 2, the light coming from the slit mask is folded by a total internal reflection prism and then reaches a dichroic which splits the light by reflecting the blue-arm passband (300–352.3 nm) and transmitting the red-arm passband (346.3–405 nm), exceeding the 305–400 nm TLR. The layout of the two arms is similar but the individual components and separations are different so as to achieve the required dispersion, magnification and image quality for the 2 passbands, using only fused silica. The f/20 collimator is a single lens. The spectrograph camera is composed of three aspheric, tilted and decentered lenses.

The large CCDs (9k × 9k or 10k × 10k) are tilted to compensate for the change in refractive index of silica with wavelength. The CCDs are cooled with Stirling coolers and controlled by ESO's 2nd-generation detector control system (NGC2).

Mechanics

CUBES requires a fairly large beam diameter of 160 mm. Consequently, the instrument envelope is also rather large compared to other Cassegrain instruments (such as X-shooter, with its 100-mm beam diameter). Scaling classical instrument designs to the required size of CUBES would exceed the mass limit of



Input spectra created.
Target magnitude: U_Vega: 18.000; V_Vega: 18.770.
Sky spectrum and atmospheric extinction imported from static model (airmass = 1.16, pwv = 30.0, moond = 0.0).

Figure 4. Top left: Simulated image of the target point spread function (PSF) on the (high-resolution) slicer focal plane, with the slice boundaries superimposed in red. Top right: Simulated raw frame for Arm 1. The six "science" slices as well as the SimCal traces are located on the upper half of the detector. The lower "AFC" half is automatically read and analysed every few minutes to measure and if necessary, actively maintain the position of a faint ThAr spectrum on the CCD (the need for SimCal and/or AFC is under study in Phase B). Bottom: Results for a flat input spectrum of $U = 18$ mag, computed with the Basic Version E2E, assuming an integration time of 3600 s. The integrated flux from the target and the sky is computed assuming the collecting area of the primary mirror of a VLT Unit Telescope and a detector integration time of 3600 s. At left, the photon balance between the target and the sky background and at right, the spectra of the target (with extinction) and background. See Genoni et al. (2022) for details.

2500 kg for VLT Unit Telescope Cassegrain instruments; a lightweight construction principle has therefore been adopted, making use of modern composite materials. The optical layout was optimised such that all optical elements of the spectrograph from slit to detector lie in a single plane, so all spectrograph optics can be mounted on a single optical bench of size 1.3 × 1.7 m. This is arguably the most stable configuration since the dispersion direction of CUBES is parallel to the stiff surface plane of the optical bench. A general focus of the mechanical design is, in fact, to minimise the effects of gravitational bending of the instrument.

In the current design, the CUBES main mechanical structure is divided into three main components: 1) a telescope adapter, that provides a stiff connection between the Cassegrain telescope flange and the optical bench assembly; 2) an optical bench that provides a stable platform for the spectrograph optics as well as for the foreoptics; and 3) an assembly to provide support for auxiliary equipment such as electronic racks, the calibration unit and vacuum equipment. This support frame is detached from the optical bench to mitigate the contribution of flexure. We are currently planning to use steel for the telescope adapter and the support frame, and a carbon-fibre-reinforced polymer (CFRP) for the optical bench. The optomechanics are currently intended to be made of aluminum alloys, for example $AlSi_40$, to improve the specific stiffness and lower the coefficient of thermal expansion (CTE) mismatch between the optomechanical parts and the CFRP bench.

Performance

An E2E simulator and an ETC have been developed to help in the definition of the current baseline design as well as in the scientific evaluation of the various observing modes (Genoni et al., 2022). The E2E provides different scenarios for the efficiency of the various components, as shown in Figure 3, and can be run in different versions according to the needs and users (for example, it can be accessed by the user in a Jupyter notebook), Figure 4 gives example of some of its outputs. For the ETC a webpage has been established through which the CUBES science community was able to test the key science cases.

Project organisation

The CUBES consortium is currently composed of institutes from five countries:

- Italy: INAF — National Institute of Astrophysics (consortium leader)
- Brazil: IAG-USP — Institute of Astronomy, Geophysics and Atmosphereic Sciences (primary Brazil partner) and LNA — National Astrophysical Laboratory (secondary Brazil partner)
- Germany: LSW — Landessternwarte, Heidelberg University Centre for Astronomy
- Poland: NCAC — Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences
- UK: STFC-UKATC — UK Astronomy Technology Centre, (primary UK partner) and Durham University Centre for Advanced Instrumentation (secondary UK partner)

CUBES adopts the standard project phasing for ESO instruments which is based on the stage-gate paradigm. Important decision points are project milestones (gates of the project) which mark the transition to a new stage when successfully completed. The entry into force of the Construction Agreement was on 15 February 2022 with expected Construction, commissioning, and Preliminary Acceptance Chile stage to be reached in 77 months, permitting the instrument to be ready for science observations in 2028.

Public engagement

CUBES offers opportunities for ambitious research programs and some of the scientific topics are related to the hottest open questions in modern astrophysics. Considering the promising discovery capabilities of the project, and the remarkable research and development behind the technology, we see crucial importance in adequately communicating the project to the lay public. Dissemination of science and technology is a fundamental part of our project and we have since the beginning defined a work package devoted to outreach. During phase A we have mainly communicated the progress of our project and the main scientific topics. We have prepared a webpage[1] that is also a useful tool for the project as a whole, and maintain profiles in various social media platforms, i.e. Facebook[2], Twitter[3], and YouTube[4]. A series of short video interviews with some of the people in the CUBES consortium have been prepared and made available on the web. As the project matures, specific activities (conferences, popular science papers, etc.) are foreseen.

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References

Alcalá, J. M. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09832-1
Ali, S. S. & De Propris, R. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09849-6
Balashev, S. & Noterdaeme, P. 2022, arXiv:2203.15582
Barbuy, B. et al. 2014, Ap&SS, 354, 191
Bristow, P. et al. 2014, Proc. SPIE, 9147, 914709
Calderone, G. et al. 2022, Proc. SPIE, 12189, 81, arXiv:2209.07294
D'Odorico, V. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09859-4
Ernandes, H. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-021-09829-2
Evans, C. J. et al. 2016, Proc. SPIE, 9908, 99089J
Evans, C. J. et al. 2018, Proc. SPIE, 10702, 107022E
Evans, C. J. et al. 2022, Exp Astron, in press
Genoni, M. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09844-x
Giribaldi, R. E. & Smiljanic, R. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09850-z
Opitom, C. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09853-w
Pasquini, L. 2014, Ap&SS, 354, 121
Smiljanic, R., da Silva, A. R. & Giribaldi, R. E. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09845-w
Zanutta, A. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09837-w
Zeitner, U. D. et al. 2022, in Exp Astron, https://doi.org/10.1007/s10686-022-09840-1

Links

[1] CUBES homepage: https://cubes.inaf.it/home

[2] The CUBES channel on facebook: https://www.facebook.com/profile.php?id=100057094524211

[3] The CUBES channel on Twitter: https://twitter.com/VLT_CUBES

[4] The CUBES channel on YouTube: https://www.youtube.com/channel/UCZqdt1MnWDUgLcYqjBTFsUA

Astronomical News

The Very Large Telescope Interferometer's (VLTI's) Auxiliary Telescopes during a colourful sunset at ESO's Paranal Observatory in Chile.

G. Hüdepohl (atacamaphoto.com)/ESO

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Interactions with the ESO Community During and After a Pandemic

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John Pritchard[1]
Henri Boffin[1]
Marina Rejkuba[1]
Martin Zwaan[1]
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Miroslav Barta[3]
George Bendo[4]
Frank Bertoldi[5]
Jan Brand[6]
Romana Grossova[3]
Michiel Hogerheijde[2]
Katharina Immer[2]
Violette Impellizzeri[2]
Sabine König[7]
Elisabetta Liuzzo[6]
Tommaso Marchetti[1]
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To accomplish its mission, ESO puts significant effort into supporting its scientific community to allow broad access to ESO's telescopes and to exploit its full technical and scientific capabilities. The pandemic-related challenges of the last few years have led to new ways of interacting with and providing support to the European ALMA and La Silla Paranal astronomical communities. Here we present some of the main events that have been organised in the last two years to achieve this goal, what we have learned, and how we foresee this will impact the future of interactions with the ESO users community.

Science user support

ESO's ground-based observatories located in Chile serve a very diverse astronomical community. The La Silla Paranal Observatory (LPO) offers observations with a variety of telescopes, instruments and observing modes in the optical and infrared, including both Visitor Mode and Service Mode observations. The Atacama Large Millimeter/submillimeter Array (ALMA) allows observations to be carried out with the interferometer in service mode. To maximise the scientific output of these observatories and to make sure that the widest range of scientists can use these facilities, user support throughout the lifetime of a project, from proposal preparation all the way to data reduction and retrieval from the archive, is essential and is consequently a significant part of ESO's activities.

For the LPO the ESO User Support Department (USD) acts as the interface between the observatory and the astronomers in the community. Several ESO staff at the ESO Headquarters support the various instruments at Paranal and collaborate closely with colleagues in Chile. With the same goal, the European ALMA Regional Centre (ARC) is the interface between the ALMA observatory and the European scientific community. Most of the direct user support for ALMA is carried out by seven nodes distributed throughout Europe, under the coordination of the central ARC at ESO in Garching. Together, these eight coordinated entities form the European ARC network (Hatziminaoglou et al., 2015; and see Zwaan et al., 2021 for a description of the ALMA organisational structure).

This level of support relies on a complex machinery that, although appreciated by the community, may be daunting for our users. In a spirit of transparency and availability, we are continuously reaching out to them to present the various tools and services available, and at the same time to provide help with improving the technical side of their proposals, preparing the observations, and reducing the data obtained with ESO telescopes and from the archive.

In the past, in-person meetings of various forms were regularly organised for the purposes of user support. These included, for example, visits by ESO staff to different Member States or community events (such as European Astronomical Society meetings) or events organised by the ARC nodes and face-to-face support at the nodes. Such meetings typically provided training on how to write proposals and information about the observational capabilities that are available or about to come into operation. Schools and workshops were organised on the Very Large Telescope Interferometer, Paranal instrument-related data reduction, ALMA data handling, and the exploitation of the ESO and ALMA archives. Most of these activities could not be continued during the 2020–2021 peak of the COVID pandemic.

In what follows we describe how the support of the ESO astronomical community has continued despite being impacted by the pandemic.

ALMA community events in the pandemic

In March 2020, in response to the pandemic, the ALMA observatory had to be shut down to guarantee the safety of its staff. In October of that year, the return towards full operations was initiated, science observations eventually resuming in March 2021. To inform the European community on the anticipated timeline of the return to operations, the implications for their science projects, and the possibilities of virtual user support in times of mobile working, the European ARC organised its first European ARC virtual community assembly in October 2020. Informative presentations by staff members from the central ARC at ESO and from the nodes in the European ARC network were followed by a question-and-answer session. This first community assembly was attended by over 150 scientists from the ESO Member States and beyond. The assembly was very much appreciated by the community, and in response the European ARC has since organised assemblies for every (pre-) announcement of a main call for

Figure 1. Still from the YouTube recording of the I-TRAIN session on self-calibration, also showing the repository of trainings covering a wide range of topics related to interferometric and ALMA data handling.

proposals (five assemblies in total so far). The assemblies included presentations on science operations, the upcoming call for proposals and user support by the network. The last assembly additionally highlighted activities related to ALMA development, with contributions from ESO colleagues based at the Joint ALMA Observatory in Vitacura. Despite the decreasing number of attendees since ALMA resumed operations, these assemblies have become a valuable way to inform the community about ongoing activities and developments, and to engage people in dialogue.

Some of the key activities carried out by the nodes in the European ARC network include providing training in the calibration, imaging, and analysis of ALMA data. The appreciation of such training, and the wish for it to continue, were reflected in community surveys about user experience and in recent interviews with ALMA users as part of the ALMA Redesign the User eXperience project (RedUX; Hatziminaoglou et al., 2022). To continuously provide such training, including during mobile working times, the European ARC network initiated the online Interactive Training in Reduction and Analysis of INterferometric data (I-TRAIN) series[1]. The one-hour tutorial sessions cover a wide range of topics of interest to the ALMA user community with the aim of helping users gain expertise in working with interferometric data. Sessions take place once a month via Zoom and consist of an interactive tutorial or presentation usually given by European ARC network staff members followed by a question-and-answer session. Since December 2020 a total of 17 sessions have been organised and have provided training on a myriad of topics, such as the ALMA imaging pipeline, data analysis techniques including self-calibration, stacking and statistical continuum determination, the exploitation of the ALMA science archive, proposal writing, and polarisation and solar observations. Individual sessions have attracted up to 150 live participants from ESO Member States and other communities. All trainings are afterwards stored on the YouTube channel of the European ARC network[2] (Figure 1), where some of them have attracted over 500 views. The I-TRAIN sessions have proven to be an effective means of structurally providing easily accessible training on a diverse range of topics to the community, while simultaneously developing an online repository of tutorials.

The nodes in the European ARC network play a key role in the preparations for the yearly ALMA deadline. In pre-pandemic times this usually consisted of in-person workshops at the local nodes, combined with node staff-members traveling to institutes and users seeking support either face-to-face at the nodes or via helpdesk interactions. The pandemic forced the nodes in the network to shift to fully online or hybrid workshops. The nodes within the network adopted a variety of approaches, including multi-day workshops on ALMA in general (Czech and UK node), multiple one-hour online sessions covering various aspects of proposing for ALMA (Nordic node), a (hybrid) proposal-preparation day via Zoom (Dutch node and Italian node) and a set of instructional YouTube videos discussing various aspects of proposing for ALMA combined with a one-hour question-and-answer virtual session (German node and Dutch node).

A key feature of ALMA support is the face-to-face support provided to users by the nodes in the European ARC network. In pre-pandemic times this support was usually in person but had to be moved entirely online. The nodes in the European ARC network quickly adapted by setting up efficient online communication platforms and remote access to the in-house servers for computing assistance. In 2021 at least 120 visits took place. Online visits have become a valuable, time-efficient, and green alternative to providing direct support with the handling and analysis of ALMA (archival) data and proposal preparation. Online face-to-face visits have become a valuable and appreciated alternative to the previous standard of in-person face-to-face visits. Requests for face-to-face visits can be made through the ALMA helpdesk[3]. Funding opportunities for visits are available through the Opticon Radionet Pilot programme[4].

To continuously support the European ALMA community the ARC network also organises scientific workshops. These activities continued in online format during the pandemic, for example with ALMA science days organised by the Dutch node Allegro for their community (Figure 2). Most notable was the recent Meeting for ALMA Young Astronomers. This three-day online conference attracted over 200 registered participants and gave early career ALMA users the chance to present their work and interact with each other (Muller et al., 2022).

La Silla Paranal Observatory community events in the pandemic

Following on from the positive experience of the LPO Users Workshop organised in 2018 (Boffin & Rejkuba, 2018), the demand for similar workshops has grown, including specific requests from the Users Committee. At the start of the pandemic, it was decided to organise a

Users Workshop with a new format: fully online, and divided into three events, each one focused on the three phases of the ESO Data Flow System (Hainaut et al., 2018). As the Call for Proposal for P107 was cancelled, the first meeting, a two-day event that took place in September 2020, focused on learning how to use the ESO Science Archive Facility and reduce ESO data. An online 'face-to-face' contact with ESO experts supporting different instruments and developing archive or instrument pipelines was provided according to individual requests. Later, in March 2021, a second online meeting helped users to learn how better to write competitive observing proposals and to use associated Phase 1 tools, such as the Exposure Time Calculator and the new p1 proposal submission tool. Finally, the third event dealt with the observing material preparation (Phase 2) process and the use of the main tools needed to prepare the observing material. This last workshop consisted of a series of talks, hands-on sessions, and 'face-to-face' meetings with ESO support astronomers.

These events took place on the Microsoft Teams platform (Figure 3) and were attended by up to 100 participants from several ESO Member States, and from other communities. The time slots were chosen to alternate between a better participation from either Chile or Australia, and the meetings were recorded, to also serve the whole community in the future. Indeed, most of the presentations and overview talks given by the ESO staff were prepared in a 'tutorial style' and form a valuable set of information composed to guide the general user at the time of proposal writing, or observation preparation or data reduction. These videos are available on YouTube[5].

A further short event was organised when the Call for Proposal for P110 was released in March 2022. This event, presenting the main news and changes in the latest Call for Proposal, for example the introduction of the Distributed Peer Review procedure, could provide the format for future events of the LPO Users Workshop. Starting from the wealth of material collected from the in-person and online events, the new instances of this programme should focus on the recent news and on new capabilities offered to the community, allowing one-to-one interactions for specific requests. Individual sessions on specific LPO issues can be arranged; requests should be submitted to the ESO Operations Helpdesk[6].

Figure 2. Participant photo from the ALMA Science Day organised by the Dutch European ARC network node Allegro for their community in December 2021.

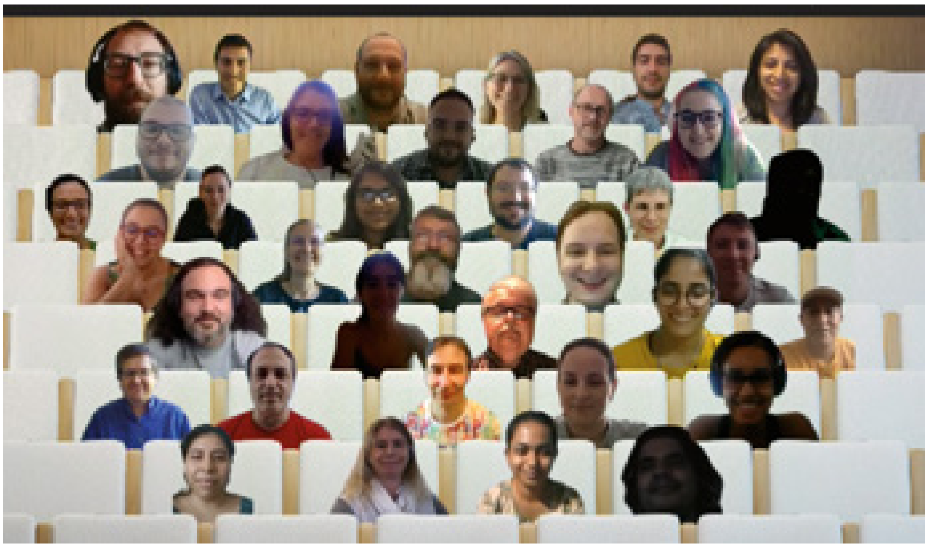

Figure 3. Screenshot from the Microsoft Teams meeting used for the LPO Users Workshop event in September 2020.

Lessons learned and the future of interaction with the ESO community

The events organised by the European ARC Network and the ESO User Support Department were positively received and well attended, with a hundred or more attendees at several events. The diversity of the attendees, both in age, affiliation (Figure 4) and background, shows that online and hybrid events are very inclusive and appeal to attendees from both inside and outside the ESO Member-State astronomer community.

We are also particularly pleased with the interest towards the videos and presenta-

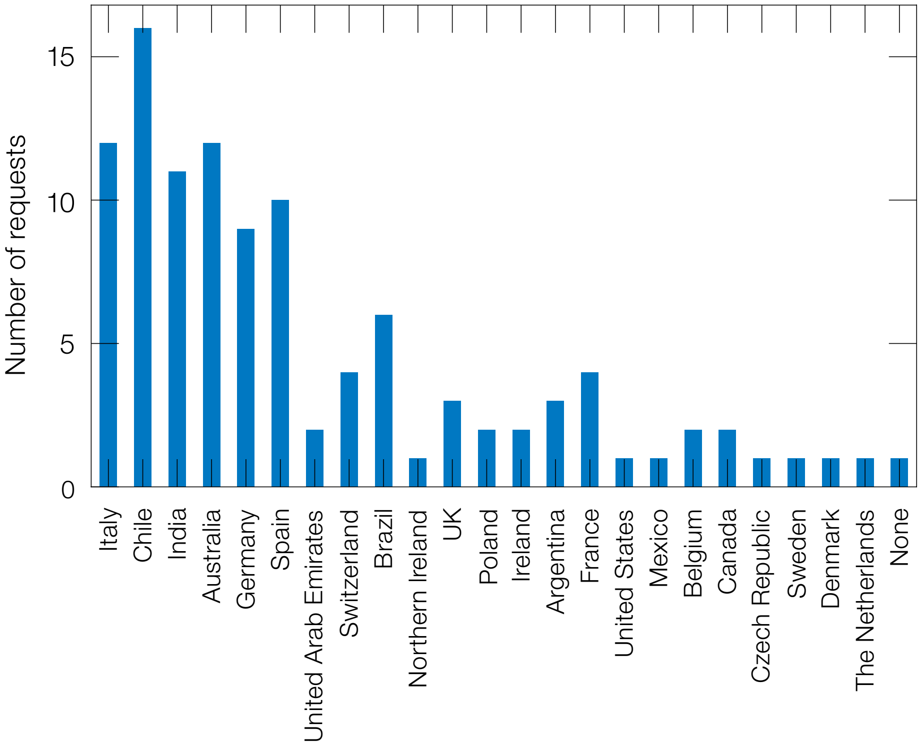

Figure 4. Country of institution for the participants of the LPO Users Workshop event held online in March 2021.

tions collected during these events, that provide a valuable repository of online tutorials on a wide diversity of topics. Videos of the sessions organised by the USD department and the sessions organised as part of I-TRAIN are all available on YouTube[2, 5]. These videos can be used for training at the user's own pace, offering a solid base of material for the community, and can also act as the basis for future interactions. The value of the online repositories is demonstrated by the high number of views, sometimes over 500, for some of the online recordings.

On the other hand, in-person interactions are needed and should be resumed, when possible, to strengthen the connection between the observatory and the community and to provide support at a personal level. Virtual events are appropriate for focused sessions to provide information or discuss specific topics, whereas in-person events are more appropriate for broader training and discussions and building new connections.

The experience gained during the pandemic has provided us a forward look towards user support in the coming years. With awareness of the carbon footprint of astronomy, and with people increasingly comfortable with attending meetings remotely, this is the right opportunity to reconsider the form in which training is provided to the ESO community. Fully online and hybrid events have the potential to continue to reach new members of the community. On the other hand, online attendance at meetings may not always result in the optimal transfer of knowledge between the observatory and user and vice versa.

A fruitful way forward may be to alternate short online meetings, focused on specific topics and accessible to everyone, with in-person events (recorded for future reference) to engage the community with the broader ESO and ALMA support and training. As many members of the ESO astronomer community use both LPO instruments and ALMA for their science, joint LPO and ALMA community assemblies, trainings and workshops are an exciting prospect to work towards. While starting to plan future events, we hope the community will engage with us to help shape future interactions. Input on topics for the various series and workshops discussed herein and suggestions for new events, formats and collaborations are always highly appreciated. These suggestions may be channelled through the ESO and ALMA helpdesks or can be discussed with your local ARC node or local Users Committee member.

The pandemic has brought new perspectives to our lives, including the way we interact with the ESO community. The lessons learned in these years will allow us to better engage the community with new forms of interaction, which could be more flexible and frequent, aiming to combine the best aspects of online and in-person interactions.

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References

Boffin, H. M. J. & Rejkuba, M. 2018, The Messenger, 172, 44
Hainaut, O. R. et al. 2018, The Messenger, 171, 8
Hatziminaoglou, E. et al. 2015, The Messenger, 162, 24
Hatziminaoglou, E. et al. 2022, The Messenger, 186, 20
Muller, S. et al. 2022, The Messenger, 187, 36
Zwaan, M. et al. 2021, The Messenger, 184, 16

Links

[1] I-TRAIN website: https://almascience.eso.org/tools/eu-arc-network/i-train
[2] European ARC network YouTube channel: https://www.youtube.com/channel/UCXsYQxxTSF-o23UP7HU_jYQ
[3] ALMA helpdesk: https://help.almascience.org
[4] Opticon Radionet Pilot: https://www.orp-h2020.eu/
[5] LPO Users Workshop videos: https://www.youtube.com/channel/UCiEvZBP_q3X6c30fevcppGA
[6] ESO Operations Helpdesk: https://support.eso.org

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Report on the ESO Workshop

Inward Bound: Bulges from High Redshifts to the Milky Way

held online, 2–6 May 2022

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Francesca Fragkoudi [3]
Anita Zanella [4]
Lodovico Coccato [2]
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With over 200 registered participants, this fully online conference allowed theorists and observers across the globe to discuss recent findings on the central structures of disc galaxies. By design, this conference included experts on the Milky Way, local and high-redshift galaxies, and theoretical aspects of galaxy formation and evolution. The need for such a broad range of expertise stems from the important advances that have been made on all fronts in recent years. One of the main goals of this meeting was accordingly to bring together these different communities, to find a common ground for discussion and mutual understanding, to exchange ideas, and to efficiently communicate progress.

Like many other meetings, this conference had to be postponed twice since 2020 because of the COVID-19 pandemic. Although the original plan was to have an in-person meeting, both the Scientific Organising Committee (SOC) and the Local Organising Committee (LOC) felt that further postponing the conference would be too detrimental. During the two years of the pandemic, the LOC had gained sufficient experience to be able to devise a format that would facilitate the meeting's intended goal of fostering discussions between the different communities.

The meeting consisted of 31 pre-recorded talks (made available to registered participants a week before the start of the conference), as well as six live sessions, held on the Monday, Wednesday, and Friday, which included 12 invited talks, four review talks, and four discussion sessions[1]. The live sessions took place in the morning and early evening in Europe, to enable the participation of colleagues from time zones in the Americas and Australia/Asia. Those sessions were recorded and made available immediately afterwards. This allowed participants in different time zones to be up to date with all the live sessions, while a Slack workspace allowed the participants to have further asynchronous interactions and discussions. We were pleased to see that this setup worked very well in fostering numerous and deep discussions as intended. The pre-recorded talks and recordings of the live sessions are now publicly available to the community[2]. In what follows we summarise some of the main discussion topics and outcomes of the workshop.

Nomenclature

An overarching discussion concerned the topic of nomenclature. We confirmed that the term 'bulge' was used to indicate different physical structures by different research teams and communities. It was generally accepted that this situation is detrimental and that raising awareness of this issue is a first step towards a solution. It was thus generally agreed that, to clearly communicate results, it is important to define from the onset what the employed nomenclature means in terms of physical structures and associated properties.

In statistical studies using large samples, the term 'bulge' usually indicates any structure within the inner kiloparsec which is not the main disc. Similarly, the term 'photometric bulge', typically employed in the context of photometric decompositions, may encompass more than one physical structure (for example, a bar and a nuclear disc). As discussed in talks such as those by Simon Driver, Adriana de Lorenzo-Cáceres and Marie Martig, the main central stellar structures often found in disc galaxies are: (i) a pressure-supported (yet, rotating) spheroid; (ii) the inner part of a bar that grows out of the disc plane and shows a boxy or peanut/X-like morphology; and (iii) a rotation-supported disc (which is not the main, large-scale galaxy disc). Respectively, they are often referred to as the 'classical bulge' (CB), 'boxy/peanut bulge' (BP) and 'nuclear disc' (ND). Some participants argued for dropping the word 'bulge' from the second and replacing 'nuclear' by 'inner' in the third. The term 'pseudo-bulge', which can refer to both BPs and NDs was said by many participants to be particularly confusing, despite being widely used.

The Milky Way

A consensus has been reached that the Milky Way has primarily a BP formed from the bar, with stellar populations born in situ (see talks by Paola Di Matteo, Francesca Fragkoudi and Melissa Ness). However, there is still a healthy debate around the ages of the stellar populations in the central regions (see talks by Tommaso Marchetti, Michael Rich, Álvaro Rojas-Arriagada and Manuela Zoccali). The contribution of the halo to the old population is clear but it is still difficult to quantify. This leaves an open question: is there still space for a low-mass, old, central spheroidal structure that is not part of the halo? In other words, is there room yet for a CB in the Milky Way? (See the talks by Cristina Chiappini and Madeline Lucey.)

In this context, we still lack a comprehensive characterisation of the most metal-poor population (with [Fe/H] < –1), from both the modelling and observational sides, even though significant progress has recently been made (see talks by Anke Arentsen, Andrea Kunder, Giulia Pagnini and Jason Sanders).

Formation scenarios

While it is still unclear what is the physical mechanism that produces BPs from the inner parts of bars (i.e., whether they form from buckling instabilities or orbital resonances), it is well established that BPs are simply the vertically thicker inner parts of bars (see talks by Sandor Kruk and Jairo Méndez-Abreu).

Likewise, there is mounting evidence that NDs form via gas inflow produced by bar-driven processes (see talks by Dimitri

Gadotti, Camila de Sá Freitas, Patricia Sánchez-Blázquez and Mattia Sormani). Nevertheless, the possibility of forming NDs via processes driven by clumps in discs at high redshift was also discussed.

A topic that sparked great interest was the possibility of forming CBs through clump-driven processes. Numerical simulations show clearly that if clumps survive feedback processes they coalesce to build a central pressure-supported spheroid; observations provide some support for this scenario (see talks by Daniel Ceverino, Miroslava Dessauges-Zavadsky, Deanne Fisher, Yicheng Guo, Thorsten Naab, Stijn Wuyts and Anita Zanella). The survival of the largest clumps can also provide constraints on how feedback works. On the other hand, while some participants argued that the clump scenario is favoured over the merger scenario to form most CBs, arguments concerning the sizes and masses of clumps suggest that mergers may still be important in forming the most massive CBs. Nevertheless, a challenge to the clump scenario is brought about by the difficulty of detecting clumps in the molecular gas distribution. Paradoxically, this would indicate high star formation efficiencies, leading to strong feedback, which in turn would dissolve clumps before they can migrate to the centre. Further, separating the effects of mergers and clump migration is still difficult (see talks by Marc Huertas-Company and Annagrazia Puglisi) and whether clumps can contribute to the formation of thick discs remains an open question. A general consensus was that more theoretical work is needed to understand the evolution of clumps and their contribution to bulge formation (for example, what is the expected range of physical properties such as the sizes and masses of bulges formed from the coalescence of clumps?).

These, and alternative, formation scenarios were also discussed in talks by Francesco Ferraro, Hua Gao, Yicheng Guo, Wako Ishibashi, Keerthana Jegatheesan, Kalina Nedkova, Sandro Tacchella and Jesse van de Sande). To some extent, a typical disc galaxy may go through all of these different processes (i.e., clump migration, mergers, bar-driven processes etc.), leading to the formation of composite bulges, where CBs, BPs and NDs co-exist (see the talk by Peter Erwin). In this context, participants also discussed that it is not clear if there is a line to be drawn between CBs and NDs. In fact, in some cases it is difficult to link observed physical properties to a single formation scenario, which can be an indication that several mechanisms play important roles in the formation of these central stellar structures.

In talks such as those by Ignacio Gargiulo, Aura Obreja and Milena Valentini, it was shown that simulations are producing realistic disc-dominated systems, although it is still not clear if they quantitatively reproduce observations. Comparing measurements from observations and simulations requires not only homogenous metrics but also understanding the systematics on both fronts, which is not trivial. In this context, a remark made by several participants concerned the apparent scarcity of massive CBs in nearby galaxies. This is in contrast with statistical studies of galaxies at intermediate redshifts, which find that CBs dominate in mass (but not in number), although it was noted that such studies suffer from relatively poorer physical spatial resolution.

A crucial piece of information comes from dynamical studies at high redshift, which find CBs (or proto-CBs) at $z \sim 1–5$, hosted by kinematically cold discs. This argues that at least some bulges and discs are already in place early on (see the talks by Luca Costantin, Federico Lelli, and Francesca Rizzo).

Future perspectives

A frequent discussion topic was the power of combining photometric analyses with results from spectroscopic studies, in particular to ascertain the kinematical properties of the stellar populations under investigation.

With a plethora of new facilities coming online in the next 2–10 years or so, the future does look bright for studies of the central regions of disc galaxies. Multi-object spectroscopy surveys to be carried out with, for example, the 4-metre Multi-Object Spectrograph Telescope (4MOST), the Multi-Object Optical and Near-infrared Spectrograph (MOONS) and by the Vera C. Rubin Observatory may in particular shed light on the metal-poor populations in the central region of the Milky Way, which will help address what is the halo contribution therein. Likewise, the expected giant leap in statistical power is bound to offer more thorough views on the nuclear disc of the Galaxy (see the talk by Oscar González).

The High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI) at ESO’s Extremely Large Telescope will bring with it the possibility of obtaining spatially resolved spectroscopy of the central regions of galaxies at $z > 1$, allowing us to directly study the formation of CBs, BPs and NDs. We will witness the unfolding of the relevant physical processes, which will provide more robust answers to the problems discussed in this conference. Of course, new questions will arise, but overall our understanding will improve, including from serendipitous discoveries that we cannot now even foresee.

Demographics

The SOC aimed at having a fair representation from the community in terms of scientific interests (i.e., Milky Way, local galaxies, high-redshift galaxies, and theory), gender, geographical regions and to some extent seniority as well. Therefore, for each of the four fields, a reviewer and three invited speakers were proposed based on discussions within the whole SOC. This led to a total of 16 review and invited talks with a 44:56 ratio of female to male speakers. On the other hand, the selection of the 31 contributed talks was performed anonymously, by hiding the author’s name and any identifying information. In so doing, as far as the gender balance is concerned, we obtained a good match between abstract submission (49% female, 49% male, 2% non-binary) and talk allocation (52% female, 45% male, 3% non-binary). A fairly good balance between abstract submission and talk allocation was also achieved in terms of geographical regions, with ratios of 56:61 (percentage of submitted and allocated talks) for Europe, 16:19 for US, 17:10 for Central and South America, 3:3 for Asia, and 8:6 for Australia. The adopted anonymous method was fairly successful in producing a balanced programme in the context of gender, geographical location and seniority, with little need for the SOC to adjust the outcome of the votes.

The workshop had a high level of participation with about 230 registered participants attending from all continents but Antarctica, with the following percentages:

- 41% Europe (Belgium, Croatia, Denmark, France, Germany, Greece, Italy, Malta, Poland, Portugal, Spain, Sweden, Switzerland, UK)
- 8% North America (Canada, US)
- 2% Central America (Guatemala, Mexico)
- 8% South America (Argentina, Brazil, Chile)
- 4% Oceania (Australia)
- 36% Asia (China, India, Iran, Japan, South Korea)
- 1% Africa (Etiopia, Nigeria)

By enabling easy and cheap access (there was no registration fee for the conference), the online format was a powerful way to reach a very diverse audience, not only in terms of geographical regions but also of career levels. In fact, about 50% of the participants were students, about 16% were postdoctoral researchers, and about 26% on a tenure track or faculty position (a fraction of participants did not specify their career level).

Acknowledgements

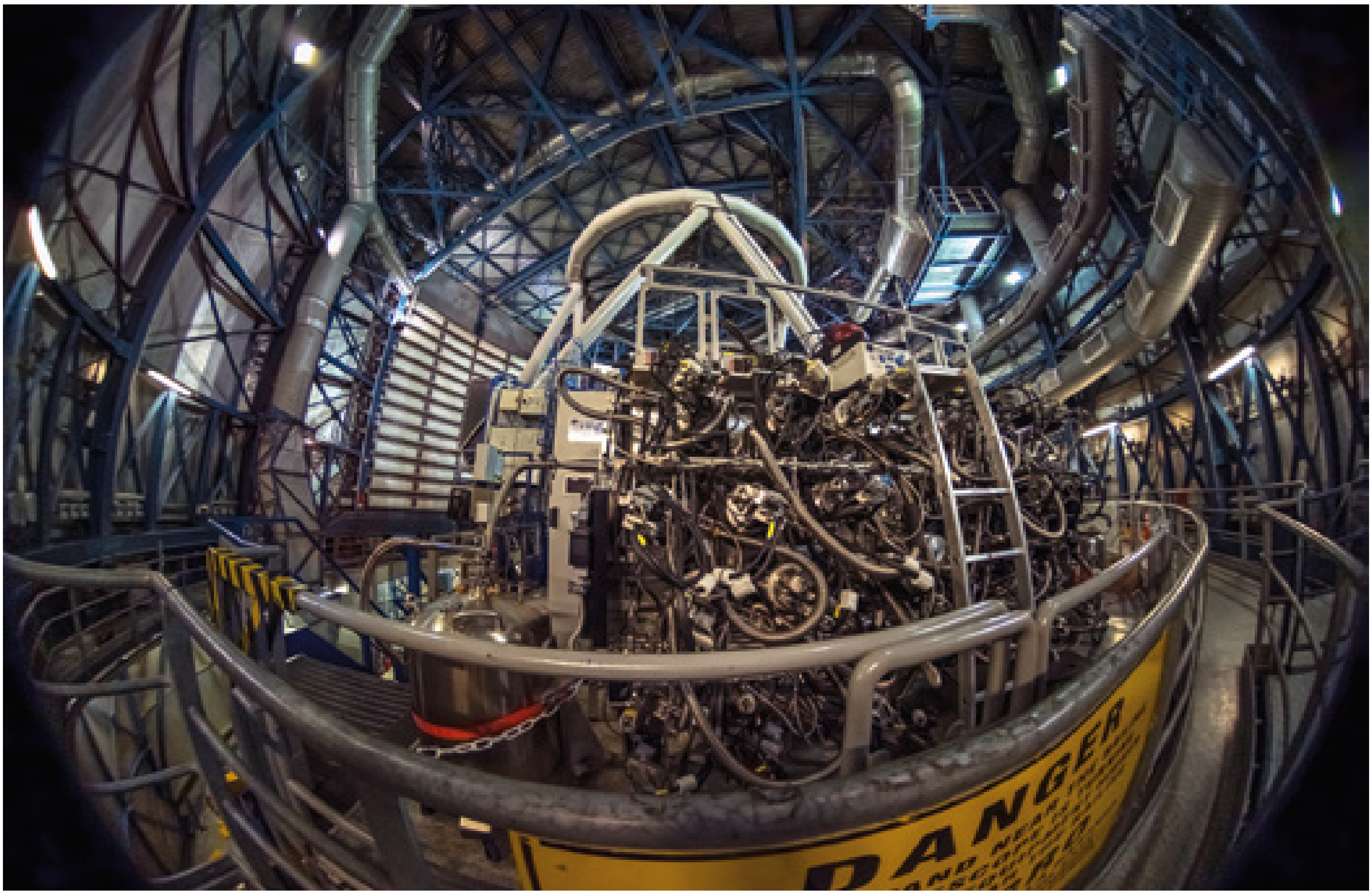
We wholeheartedly thank Tutku Kolcu, Alonso Luna and Nelma Silva for their invaluable support and dedication to making this a successful meeting. We are grateful to the SOC members for their sustained commitment during these difficult times, as well as for their key contribution and insight as chairs of several discussion sessions.

Links

[1] Link to workshop programme: https://www.eso.org/sci/meetings/2022/BULGES2022/program.html

[2] Link to access all workshop recordings (i.e., review, invited and contributed talks, as well as the discussion sessions): https://www.eso.org/sci/meetings/2022/BULGES2022/restricted.html

Zdeněk Bardon/ESO



Is this tangle of cords and hoses a machine from the movie The Matrix? You can stay calm: even though the sign says “danger”, what may look like a threatening machine is actually the Multi Unit Spectroscopic Explorer (MUSE) instrument on ESO’s Very Large Telescope (VLT) at Paranal Observatory. MUSE is one of the largest instruments at the VLT and is connected to one of its four 8.2 m telescopes, Yepun.

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Report on the ESO Workshop

Reproducibility and Open Science in Astronomy

held online, 10–12 May 2022

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Reproducible and open research lies at the heart of science, for both practical and philosophical reasons. To validate results, researchers must be able to access the data and software used to produce them. Meanwhile, as a public good, the outcomes of (publicly-funded) research should be freely available. These were the main topics of the ESO workshop Reproducibility and Open Science in Astronomy, which was held online on 10–12 May 2022, hosted in Santiago, Chile. The goal of the workshop was to discuss the relevance of reproducible workflows in astronomy and potential pathways for the astronomical community. During the workshop the speakers and participants shared examples of reproducible work as well as tools and techniques for improving reproducibility and for mining astronomical data. All talks, tutorials and discussion sessions were recorded and can be viewed online.

The way we do science is constantly evolving and is currently undergoing a paradigm shift, partly driven by the general tendency towards openness in society and the idea that the outcomes of publicly-funded science should be freely available. The ever-increasing volume and complexity of astronomical data and simulations call for accessible methods to verify and reproduce results. Existing and upcoming large facilities (for example, the Atacama Large Millimeter/submillimeter Array, the Square Kilometre Array, the Sloan Digital Sky Survey 5, Vera C. Rubin Observatory, ESO's Extremely Large Telescope and other in this category) provide or will provide us with enormous volumes of data, promising revolutionary scientific capabilities. To handle these large datasets, we can no longer rely on small computing facilities and will need to move analyses to science platforms. It therefore makes sense that now is the time to adapt our approaches to science. Large collaborations aren't alone in benefitting from open science and reproducible research; any individual researcher might struggle to recall details of a previous project. Incorporating open and reproducible workflows at the outset of research could help promote efficient retrofitting and new developments.

The metrics currently used to reward 'excellence' in astronomy — and science in general — do not always benefit open science. Publishing many papers that focus on results and not methods is not beneficial to astronomy in the long term. Promoting alternative metrics to evaluate candidates during hiring processes is important if we are to shift the community's focus.

Aims of the workshop

The workshop Reproducibility and Open Science in Astronomy (ROSA 2022) aimed to share examples of reproducible work as well as tools and techniques for improving reproducibility or mining astronomical data. The experts, brought together by the scientific organising committee (SOC), focused on the questions:

1) What are reproducibility and open science?
2) How to make research reproducible?
3) What are the objectives, benefits, and difficulties of reproducibility?

We designed the workshop programme[1] to be as interactive as possible, achieved by organising two one-hour discussion sessions and leaving ample time after each talk for questions. The workshop included tutorials about data platforms, such as ESA datalabs[2], the Spanish Virtual Observatory[3] (SVO), the Canadian Advanced Network for Astronomy Research[4] (CANFAR) and the Square Kilometre Array Observatory[5] (SKAO). Discussions focused on how to share data and the future of open science. To avoid screen fatigue and to cater to multiple time zones the workshop was restricted to five hours each day. All the talks were recorded, allowing participants to view them at their own pace.

The SOC aimed to reach a wide and varied audience. Since ROSA 2022 was an online workshop, there were no travel costs for participants. The workshop itself was free of charge for the participants, enabling us to reach beyond those already acquainted with the topic and in particular allowing a large number of students to attend.

Summaries of talks and highlights from sessions

Introduction to the workshop

Lourdes Verdes Montenegro gave the introductory talk, getting us all up to speed with an overview of current challenges in reproducible research and possible solutions to them. She focused on the current problems with metrics, introducing alternative metrics (for example, the Declaration on Research Assessment, DORA[6]) and the challenges of big data.

Scientific publishing

The second talk, by Chris Lintott, focused on scientific publishing and how a system of paywalls and publishing fees impedes open science. Open Access is a good development, but if its costs fall exclusively on researchers this creates anger, especially when journals make large profits. One solution is to demand a revolution within science or to publish in open journals such as The Open Journal of Astrophysics. However, Chris pointed out that, in contrast to other fields, astronomy journals are community-owned and all of the same quality and standing, so there are not the same commercial pressures or degree of competitiveness. This means that it is easier for astronomy journals to amend their policies without fear of negative impacts; many of the well-known astronomy journals are now changing their policies on citing software and storage of data.

Chris Erdman gave us a roadmap for sharing models, software, and code. Chris emphasised the benefits of publishing and indexing your software. You get a persistent copy of your software while improving the reproducibility, discoverability and awareness of your research. Chris also gave the very valuable tip to take your entire team to workshops, so everyone is on the same page.

Alice Allen, Editor of the Astrophysics Source Code Library[7] (ASCL) elaborated on the topic of citing and indexing software. The ASCL registers code used in articles, provided that the source code is freely available for download. They also carry out research projects and analyse what happens to the software over time by testing weblinks (Allen, 2021). For instance, 11% of the software published in 2015 was unavailable; when the same links were tested in 2021 the number of broken links had increased to 20%. On the bright side, Alice told us that thanks to many recent changes in the community resources and broad efforts across different disciplines, it has become much easier to index and track software.

Jelle de Plaa told us about the steps taken at the Netherlands Institute for Space Research (SRON) to make research within the institute more reproducible. At SRON they formulated a data management plan and formed a team of data stewards to assist the researchers. The team created reproduction packages and regularly organises workshops within the institute. Jelle provided templates of the reproduction packages used at SRON[8].

Big data science

Mohammad Aklaghli's talk "Big data, big responsibility" focused on the long-term preservation of data and code. To reproduce a research project one needs to know details about the software, for example versions and the configuration environment of the code. Compute containers (for example, Docker[9] and Singularity[10]) may seem like good solutions, but these facilities may not be supported forever. These binary files are expensive to archive because of their size and, because they are binary files, they are not searchable without installing them first. Mohammad presented Maneage[11], a framework which solves this problem using simple plain text files.

Many large projects find that they can no longer bring the data to the researcher because datasets are simply too large; instead, researchers need to go to the data. Science platforms providing all the required analysis tools can be the solution.

The workshop programme included a number of talks and tutorials on data platforms.

- Alex Clarke showed us how regional data centres will provide SKAO data to users. The SKAO runs data challenges (CDAs) aiming to familiarise the scientific community with the data products and tools to extract results from them (Bonaldi et al., 2021). The SKAO have organised two challenges so far and Javier Moldon gave further details of CDA2. To encourage reproducibility, submissions received awards if they adhered to reproducible practices. Javier concluded that extensive community training is required to develop familiarity with reproducibility software.
- Vicente Navarro and Marcos Lopez-Caniego gave us a tutorial on the ESA datalabs science platform (Arviset et al., 2021). The platform has been running a closed beta since March.
- Toby Brown presented ARCADE (Major et al., 2019), an Interactive Science Platform in CANFAR and gave us a live demo. Stephen Gwyn gave a tutorial on creating tables in CANFAR with the Your Catalogues (YouCat) facility.
- Stefania Amodeo introduced the European Science Cluster of Astronomy and Particle physics ESFRI research infrastructures (ESCAPE[12]) project. It provides open access long term data usability for astronomy and particle physics with the aim of bringing different communities together. Stefania focused on Virtual Observatory data and gave a demonstration of MOCpy, a Python library allowing the easy creation, parsing and manipulation of MOCs (Multi-Order Coverage maps).
- Guiseppina Fabbiano talked about the virtual observatory, a multi-wavelength, multimessenger, digital sky that can be searched, visualised and analysed. She showed that the data available in the virtual observatory often get reused in different research projects, which shows how important it is to make data publicly available.
- In a series of tutorials by Fran Jiménez-Esteban, we were introduced to the data platform of the SVO.
- Magda Arnaboldi gave a talk about the ESO Phase 3 archive[13]. She discussed how the archive can ensure the legacy value of science data products.
- Carlo Manara showed the advantages of making data from the ODYSSEUS[14] collaboration publicly available. This resulted in many additional projects on top of the original science plan.
- Jakob Nordin presented the software platform AMPEL (Nordin et al., 2019), which facilitates reproducibility in transient astronomy. The software platform fully enables Code-to-Data for the time domain.

Discussion sessions

Aside from the talks and tutorials, we reserved two hours for discussions about sharing data and the future of open science. All the talks and tutorials and a summary of the discussion sessions are available on the workshop's YouTube channel[15].

Main conclusions from the workshop & ways forward

After an intensive three days, we all concluded we had learned a lot about reproducible and open research. The participants came up with excellent recommendations and lots of ideas for improvement. These ideas were focused not only on individual researchers but also on how we can convince the institutes where we work and the journals in which we publish to make necessary changes.

During the workshop we saw some great examples of how science is becoming more open and reproducible on almost every scale and how astronomy is playing a pioneering role. Journals are making an effort to include datasets and software with published papers, large observatories provide understandable pipelines, universities and institutes are developing policies on how their data and work are stored and researchers are providing their codes and data.

However, there is still room for improvement. Many research papers are not yet reproducible and the projects that are reproducible today may not be a few years from now, as methods may become obsolete. We hope ROSA 2022 will encourage more reproducible research projects and we invite everyone to (re-)watch the talks and tutorials.

Demographics

The SOC sought fair representation from the community. We paid attention to all aspects of the workshop, such as the process of inviting speakers and selecting contributed talks. The SOC agreed that the emphasis of the workshop would lie on the invited talks and tutorials. However, the programme did include five slots for contributed talks. We informed anyone applying to give a contributed talk that the space in our programme would be limited, but that they were welcome to submit abstracts. We were happy to receive seven abstracts from which we selected five for the workshop. The abstracts were ranked in quality by the SOC, who only considered the text of the abstracts to avoid biases from other information.

There were 109 participants. Attendees came from six continents (all but Antarctica), with the following percentages:

- Latin America: 17%
- Asia: 24%
- North America: 8%
- Europe: 48%
- Africa: 2%
- Australia: 2%

With 31% students, 15% postdocs, 34% staff and 23% other participants, we had a good representation of the community. Of our speakers, 27% were female and 73% male. This ratio seems to be reflected in the participants among which 29% were female, 2% non binary, 60% male and 9% left the answer blank. We note that of all seven contributed abstracts we received, six were submitted by male speakers and one by a female speaker. In the case of the invited talks we made an effort to obtain the best possible gender balance. However, there is room for improvement concerning the gender balance of the tutorials. Both the ‘Local’ Organising Committee (LOC) and the SOC were spread all over the world from Taiwan to Chile and we organised the event over several time zones.

Acknowledgements

We thank all the participants in ROSA 2022, and especially the speakers, LOC and SOC members, and the many participants who provided lively discussions and shared additional information and references during the workshop. We would especially like to thank Leslie Saldias for organising the logistics of the event.

References

Allen, A. 2021, arXiv:2111.12574
Arviset, C. et al. 2021, LPI Contributions, 2549, 7014
Bonaldi, A. et al. 2021, MNRAS, 500, 3821
Major, B. et al. 2019, ASP Conf. Ser., 523, 277
Nordin, J. et al. 2019, A&A, 631, A147

Links

[1] Workshop programme: https://www.eso.org/sci/meetings/2022/REPRODUCIBILITY2022/programme.html
[2] ESA datalabs: https://datalabs.esa.int/
[3] Spanish Virtual Observatory: https://svo.cab.inta-csic.es/main/index.php
[4] CANFAR: https://www.canfar.net/en/
[5] SKAO: https://www.skao.int/en
[6] DORA: https://sfdora.org/
[7] ASCL: https://ascl.net/
[8] SRON reproduction package template: https://github.com/jdeplaa/open-data-template
[9] Docker container: https://www.docker.com/
[10] Singularity container: https://docs.sylabs.io/guides/3.5/user-guide/index.html
[11] Maneage: https://maneage.org/
[12] ESCAPE: https://projectescape.eu/
[13] ESO Phase 3 archive: https://www.eso.org/sci/observing/phase3.html
[14] ODYSSEUS: https://sites.bu.edu/odysseus/
[15] Conference YouTube page: https://www.youtube.com/channel/UC34OkFIBFtCHpjkNOOM7HOA/videos

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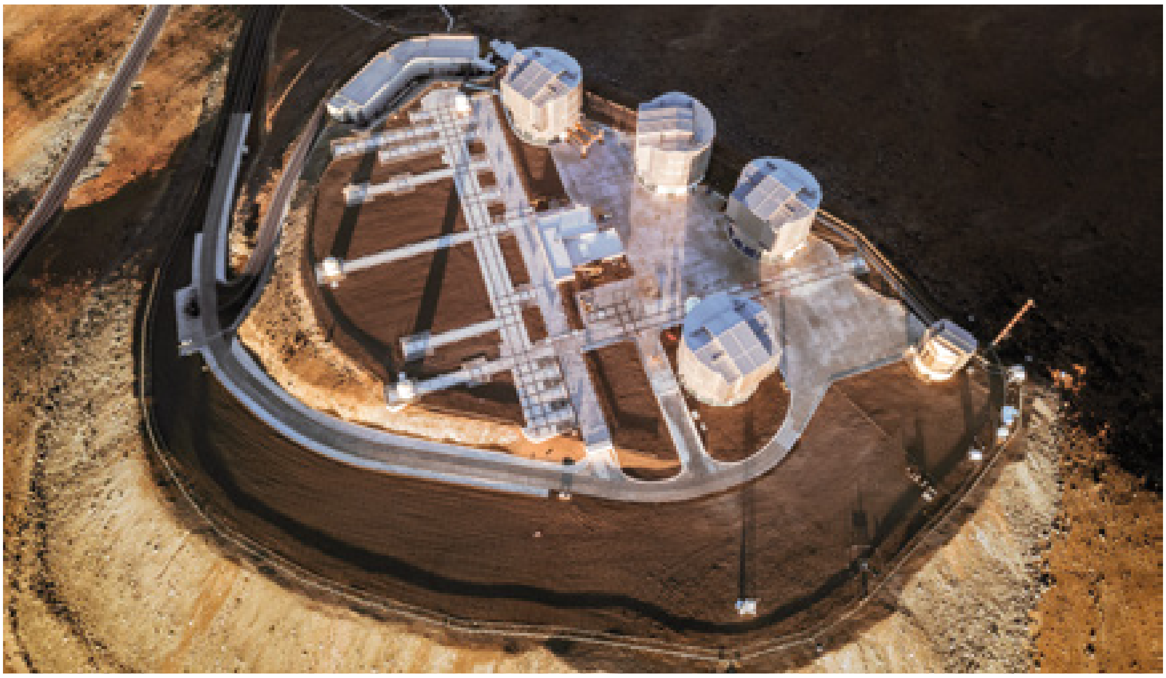
ESO/Gerhard Hüdepohl

ESO’s Very Large Telescope (VLT) seen from above.

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Fellows at ESO

Belén Alcalde Pampliega

Since childhood I have been fascinated by Earth and space exploration and eager to understand how things, nature, and even (human) brains work. But almost everything else, from drawing to running, has also piqued my interest. I grew up in a small town in the north of Spain where, like hundreds of other children, I dreamed of one day becoming an astronaut. I took this dream very seriously and knew by heart details such as lunar geography or the dates, spaceships and astronauts that had participated in each lunar landing. However, I must admit that choosing a career was not easy for me. I was full of doubts. I wanted to have it all at once. Engineering, maths, architecture, physics, and aeronautics were the top five.

As an enthusiastic and extremely active person, I found my balance by combining a strong formal education with the fulfilment and harmony I experience when I push my limits while "playing" in nature. The wilderness also awakened in me a deep interest in the mysteries hidden in the starry night, something that became especially important during the last year of my engineering studies when I lived in Hämeenlinna, Finland. The clear, unpolluted sky is the perfect window onto the Universe, not to mention the magic of the Northern Lights. Back then, there was always a book on astronomy on my nightstand.

After obtaining my engineering degree and while studying for a master's in product design in Barcelona, I decided to take my hobby more seriously and I enrolled in the Distance Learning University of Physics while working to fund a two-year master's in astrophysics. It was a time of packed, exhausting and endless days, but I believe it was the right decision. As a person with endless curiosity, I discovered a space in the world of science where I could unleash my curiosity by sharing my questions and finding, even if only partially, some answers. My master's thesis involved the development of a simulator for the design process of the optical Integral-Field Unit and Multi-Object Spectrograph MEGARA, now installed at the largest telescope in the world, and fibre spectrographs in general. My thesis advisor, Armando Gil de Paz, was not only a great advisor, but also a role model in many ways. He is one of those inspiring people who helps you work towards goals you think you are not capable of.

This experience was key to my being offered the Australian Astronomical Optics (AAO) Instrumentation Fellowship, where I conducted the experiment "Use of coherent guide bundles for adaptive-optics wavefront sensing" under the direction of Michael Goodwin. Since then, my heart has been divided between science and instrumentation. This short research stay in Australia was extremely rewarding, both scientifically and personally. Australia is a wild, vibrant, multicultural country where I was able to rediscover the night sky. At the extremely dark Siding Springs Observatory, only the red-tinted eyes of emus and kangaroos occasionally glowed beneath the awe-inspiring sight of the Large and Small Magellanic Clouds. Back in Sydney, I also fondly recall a lively conversation about 'current' challenges in astronomy with a visiting astronomer during a science lunch. It was only at the very end of the conversation, when he was summarising his science and inviting me to the lecture he would give in Spain a few months later, that I found out his name. The gentle, quiet, blue-eyed man was Brian P. Schmidt, who had been awarded the Nobel Prize in Physics in 2011. It was a lesson in humility that I will never forget. Right after that, I joined the Young Graduate Trainee Fellowship at the European Space Agency (ESA), where I searched for binary systems and movement groups in the framework of the Virtual Observatory (VO). There I met Benjamín Montesinos, the current President of the Spanish Society of Astronomy, who was a source of inspiration for me.

Immediately afterwards, I started my PhD thesis, which was supervised by Pablo G. Pérez-González at the Complutense University of Madrid and by Guillermo Barro at UC Berkeley. This gave me the enriching opportunity to experience the scientific life in the astrophysics department at Berkeley during my research stays. In addition, during the latter part of my PhD, I was able to gain hands-on experience as a support astronomer at the 2.5-metre Isaac Newton telescope at Roque de los Muchachos Observatory on the island of La Palma, thanks to an STFC grant. This was a rewarding and enlightening experience; observatories are to me what playgrounds are to children.

My PhD thesis, which I defended in July 2020, aimed to build a complete census of massive galaxies in the early Universe by adding a hidden population of extremely red sources. This elusive population, which poses a challenge to current models of galaxy formation and evolution, is extremely faint at optical wavelengths because of dust obscuration. However, the light absorbed by the dust is re-emitted at (sub-)millimetre wavelengths. Therefore, my next step was to learn everything I could about submillimetre astronomy and interferometry. My keen interest in observational astronomy along the entire electromagnetic spectrum was key in my decision to apply for the ESO fellowship.

I have been an ESO/ALMA Fellow since October 2020, combining my research activities with the operation of the Atacama Large Millimeter/submillimeter Array (ALMA). Because of the pandemic, it took me a long time to make it to the Array Operations Site on the Chajnator Plateau, but the experience was definitely worth the wait. It is not just about enjoying this impressive array in a lunar-like landscape, but more importantly about having the opportunity to share it with experts (of which astronomers are only a tiny fraction) who are always willing to gift a little of their time to answer your questions and share their knowledge. I feel privileged!

Łukasz Tychoniec

How were the Sun, Earth, and planets formed? How did life originate on Earth? Those are the questions that keep me curious. How did I decide that answering them should be my daily job?

Since I was a kid I have been a keen observer of the night sky. I had a small telescope in my hometown of Nowogard in Poland, and we played a lot with it with my father, mostly looking at planets and the Moon. What probably helped were relatively dark skies, compared with most of the places I lived in afterwards.

Comparing my amateur observations to what I saw on the news, with the Hubble Space Telescope and the Very Large Telescope (VLT) delivering stunning images, I realised that I won't ever afford a telescope that would show me the deepest secrets of the Universe and if I want to get my hands on those facilities, I should become a professional astronomer. That's why I enrolled in astronomy at Adam Mickiewicz University in Poznań. There I met Agata Karska who had just arrived in Poznań with data from the Herschel Space Observatory and I finally could reach for what I've always wanted: to do science with a space telescope.

That's how I also started studying star and planet formation, as Herschel excelled in far-infrared observations of star-forming regions. The thing about studying star formation is that it is really difficult to catch forming stars in the act — they are usually hidden deep inside the clouds from which they form. Luckily, by moving to longer wavelengths we can peer through those clouds and witness the miracle of stellar birth. That's why I also explored much longer wavelengths than infrared in the following years: first, during a summer project at Leiden Observatory with John Tobin, when I looked at protostars with the Very Large Array (VLA) at centimetre wavelengths. This became the topic of my master's thesis which I defended in Poznań in 2016.

I spent a lot of my studies working as a barista (a professional coffee maker) which turned out to be a fantastic hobby. Even though I couldn't pursue this career full-time, visiting coffee places and talking to other baristas is still my main activity, anytime astronomy pushes me to new locations. What I didn't know early on, is that astronomy is an incredibly adventurous career and it's amazing how many places it lets you live in and visit. That is an opportunity I'm very grateful for.

When the time came to choose a place for PhD studies, Ewine van Dishoeck in Leiden invited me to work on preparations for the James Webb Space Telescope (JWST) observations. It was a dream come true for me, to be able to take a front seat and conduct research using world's most powerful space telescope. It turned out also to be a lesson in patience, as I'm still waiting for the data we expected to arrive in 2018. As I write we are days away from the first full set of JWST observations — a momentous and probably the most exciting moment of my career so far.

During my PhD I wasn't just idly waiting for JWST data — I pursued observations of protostarts with the Atacama Large Millimeter/submillimeter Array (ALMA). I focused specifically on jets and outflows from those young stars and how they affect the chemical composition around them. Aside from being a powerful astrochemistry machine, ALMA is also very sensitive to cosmic dust. I used VLA data from my master's project and combined it with ALMA to weigh the dust that is surrounding forming stars. I found out that the protoplanetary discs in the youngest objects are more massive than their evolved counterparts. By comparison with the masses of the exoplanetary systems that were discovered in thousands over the past three decades, I showed that the formation of giant planets needs to begin very early, likely in the first 100 000 years after the beginning of the formation of the host star.

I finished my PhD in 2021 and took a position as a research fellow at ESO. Being amazed by ALMA's capabilities and awaiting data from JWST, ESO seemed a natural place for me to pursue my career as an observer. I wanted to further understand the complexity of interferometric observations with ALMA and I wanted to surround myself with experts on ESO facilities, which would help me to create exciting synergies with JWST. ESO is a fascinating mix of people doing research and those designing, building and organising the work of the telescopes that make research possible.

As a Fellow, I spend a fraction of my time on functional duties for the observatory. I decided to work for ALMA since it allows me to understand better how the observatory that I so keenly used for the past few years operates. Specifically, I work on one of the development studies which is meant to bring ALMA in new directions. In September I will finally visit ALMA for the first time and work there as an astronomer on duty.

With JWST finally delivering data, ESO's Extremely Large Telescope coming up in a few years, and ALMA at its full capacity we are probably in the most exciting decade of observational astronomy and I'm beyond happy to spend a part of it at ESO.

This image shows an infrared view of Sagittarius B1, a region close to the centre of the Milky Way, imaged with ESO's Very Large Telescope (VLT) in Chile. The centre of our galaxy is an exotic environment, densely populated with stars, and has been suggested to have more star formation than any other place in the Milky Way. But so far we have only found less than 10% of all young stars we expect there. Where are the others?

ESO/Nogueras-Lara et al.