The Messenger

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NIRPS Joins HARPS: Setting New Standards at Infrared Wavelengths

Artificial Intelligence Usage by ESO Telescope Users

The Promises and Challenges of the ALMA Wideband Sensitivity Upgrade

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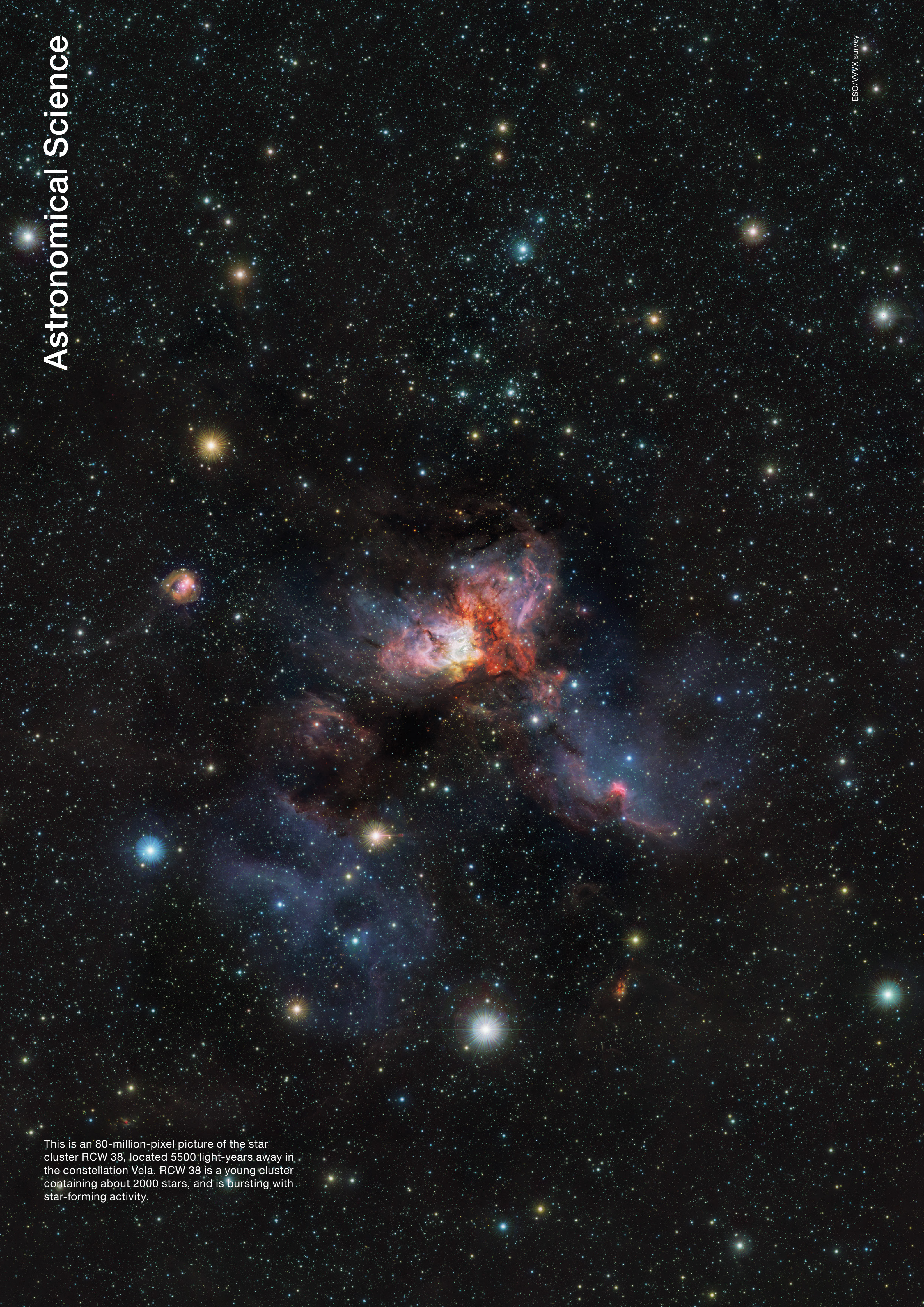
Front Cover: This image, taken with the VLT Survey Telescope hosted at ESO's Paranal Observatory, shows the beautiful nebula NGC 6164/6165. The nebula is a cloud of gas and dust surrounding a pair of stars called HD 148937. In a new study using ESO data, astronomers have shown that the two stars are unusually different from each other — one appears much younger and, unlike the other, is magnetic. Moreover, the nebula is significantly younger than either star at its heart, and is made up of gases normally found deep within a star and not on the outside. These clues together helped solve the mystery of the HD 148937 system — there were most likely three stars in the system until two of them clashed and merged, creating a new, larger and magnetic star. This violent event also created the spectacular nebula that now surrounds the remaining stars.
Credit: ESO/VPHAS+ team. Acknowledgement: CASU

S. Otarola/ESO

A solitary antenna points timidly at the Moon. But this is not some lonesome telescope, but one of the 66 antennas that together make up the impressive Atacama Large Millimeter/submillimeter Array (ALMA), operated by ESO and its international partners.

Astronomical Science



This is an 80-million-pixel picture of the star cluster RCW 38, located 5500 light-years away in the constellation Vela. RCW 38 is a young cluster containing about 2000 stars, and is bursting with star-forming activity.

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Exploring the Star Clusters in the Centres of Galaxies with MUSE

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Massive star clusters are ubiquitous in the central regions of galaxies. For example, nuclear star clusters are present in most galaxies, and bulge regions can host globular clusters. Even though these star clusters are bright, studying their properties is limited by the underlying galaxy light. Here we discuss how integral-field spectroscopy with the Multi Unit Spectroscopic Explorer (MUSE) has enabled studies of the inner globular cluster systems of massive galaxies and how MUSE has allowed us to constrain the formation mechanisms of nuclear star clusters.

Introduction

The central regions of galaxies are home to many morphological structures, such as discs, bars or bulges, shaped by various processes. Within these structures, massive star clusters such as nuclear star clusters (NSCs) and globular clusters (GCs) can be embedded. Even though NSCs and GCs are both dense star clusters with millions of stars packed tightly together — and therefore inherently bright — studying those objects within the central regions of galaxies is challenging, owing to the underlying galaxy background. In photometric studies, the galaxy light is often modelled and subtracted to derive the colours and sizes of NSCs and GCs; however, such an approach is not possible with slit or multi-object spectroscopy. For this reason, spectroscopic studies of GC systems are usually limited to the outer regions of galaxies (for example, Forbes et al., 2017), and slit spectroscopy of NSCs is preferably done on bulgeless spirals or faint dwarf galaxies, where it is assumed that the host galaxy is not contributing significantly to the light in the centre (for example, Paudel, Lisker & Kuntschner, 2011; Kacharov et al., 2018).

The high spatial sampling combined with the wide field of view provided by the Multi Unit Spectroscopic Explorer (MUSE) instrument at the VLT has allowed us to circumvent these limitations. With MUSE data of nearby (< 50 Mpc) galaxies it has become possible to extract and analyse the spectra of star clusters nestled within the central regions of galaxies. As the host galaxy can be studied from the same data, a direct comparison between the stellar population and the kinematic properties of the host galaxy and its star clusters becomes possible. With such an approach, the inner star cluster systems of galaxies can be explored, and even the formation pathways of nuclear star clusters can be unveiled.

Probing inner globular cluster systems

GCs are dense star clusters, characterised by old stellar ages, which makes them powerful tracers of galaxy assembly and evolution. GCs within the bulge region of the Milky Way have recently been discussed as fossil remnants of bulge formation (Ferraro et al., 2021), but less is known about the GC populations in the inner regions of massive galaxies.

Fahrion et al. (2019) described the approach of extracting and analysing star cluster spectra from MUSE data using MUSE observations of FCC47 (NGC 1336), a nucleated elliptical galaxy in the Fornax cluster at a distance of 20 Mpc (Figure 1). Line-of-sight velocities of 24 GCs and metallicities of five GCs were measured. Fahrion et al. (2020b) then applied this method to data of 32 Fornax galaxies that were observed as part of the ESO Large Programme Fornax3D (Sarzi et al., 2018). In total, 733 GCs with reliable velocity measurements were found. For a subsample of 238 GCs metallicity measurements were also possible. With this sample, a non-linear translation between Hubble Space Telescope colours and metallicities was found (Fahrion et al., 2020c) and spectroscopic catalogues at larger radii from multi-object spectroscopy could be added (for example, Chaturvedi et al., 2022). Moreover, with this sample it was possible to test how well GCs trace the properties of the underlying host galaxy. Comparing the rotation amplitude and velocity dispersion of the GC systems with the rotation and dispersion of the host galaxies, it was shown that the red GCs in particular are good tracers of the motion of galaxy spheroids. Additionally, comparing GC metallicities with the host's metallicities at the projected positions of the GCs showed that these red GCs also follow the metallicity profile of the host.

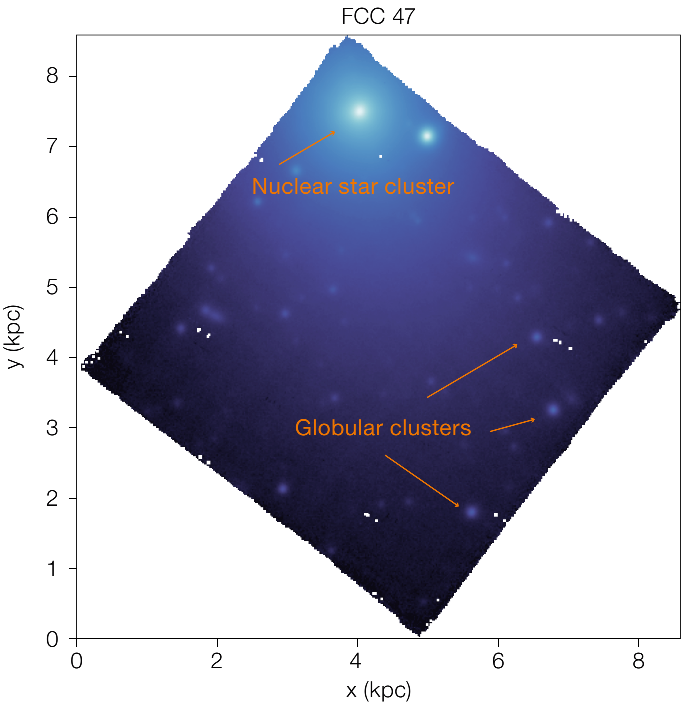

Figure 1. MUSE image of FCC 47 in the Fornax cluster with NSC and GCs highlighted.

Constraining nuclear star cluster formation

The formation of NSCs can be a complex process and typically two main pathways are discussed (see Neumayer, Seth & Böker, 2020 and references therein, and Figure 2): (i) formation through star formation directly in the galaxy centre, following the accretion and compression of gas, and (ii) via the mergers of massive star clusters. While these star clusters can be young clusters formed very close to the galaxy centre, traditionally the inspiral of GCs has been considered. In this way, NSC formation might be connected to GCs.

The *in-situ* or central star formation scenario depends on the mechanisms to funnel gas into the central region. Formation directly in the galaxy centre then has consequences for the NSCs formed in that way. For example, it can explain the presence of very young stars seen in the NSC of the Milky Way (for example, Schödel et al., 2020), and the formation from gas through dissipative processes explains the sometimes elongated, rotating and young NSCs in nearby spiral galaxies (Seth et al., 2006). As this process depends on the star formation activity in the galaxy centre, the NSC formed can show a complex, extended star formation history and can reach metallicities exceeding those of typical GCs as a result of being formed from already pre-enriched gas and metal-retention in the deep potential well of the galaxy centre. Complex star formation histories and high metallicities, however, can also be created when NSCs form through the rapid in-spiral of star clusters formed in the central region that then spiral in directly (for example, Guillard, Emsellem & Renaud, 2016), which might be an important channel at high redshift.

On the other hand, formation through the mergers of GCs is a singular way to explain metal-poor populations within NSCs, for example as in the Milky Way (Do et al., 2020). This channel, in its purest form, only considers the dry merger of GCs and therefore no additional star formation is considered. As such, the NSC formed is expected to reflect the properties of GCs, which are characterised by old populations and low metallicities.

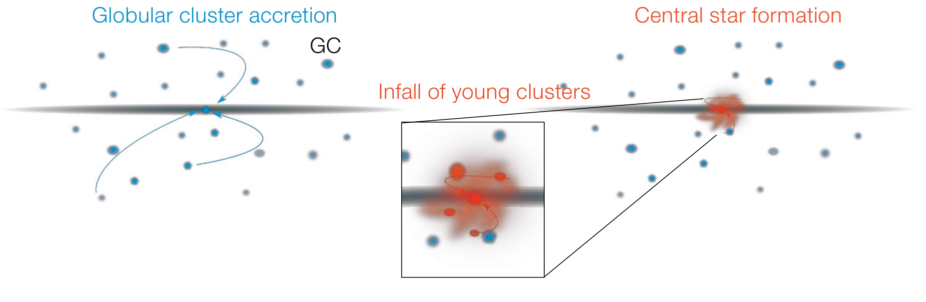

Figure 2. The two most discussed NSC formation channels: formation through the accretion and inspiral of GCs (left), and formation directly in the galaxy centre through in-situ star formation (right). In the latter, young star clusters might be formed first in the central region and then quickly spiral in (see the zoom-in).

Dominant NSC formation channel

While there are indications that the NSC formation channel depends on galaxy mass and type (see Neumayer, Seth & Böker, 2020 for a discussion), to understand this process in individual galaxies the properties of NSCs and their hosts must be compared.

Using a similar approach as for the GCs, we can use MUSE data to study the stellar population properties of NSCs from background-cleaned spectra and compare them to the properties of the underlying host galaxy. This allows us to compare, for example, the NSC metallicity with that of the host. As a first example that this approach can unveil the dominant NSC formation mechanism, Fahrion et al. (2020a) studied two dwarf spheroidal galaxies observed with MUSE. In both cases, very metal-poor NSCs were found, even less enriched than the host galaxies. In the case of one dwarf galaxy, KK 197, the NSC even shares its low metallicity with a GC found near the centre, suggesting a formation from GCs spiralling into the centre. Building on this, Fahrion et al. (2021) then presented a larger sample of 25 early-type galaxies, mainly in Fornax, spanning a range of galaxy masses from 10^7 to 10^{11} $M_\odot$. Considering the metallicity differences between NSCs and hosts as well as NSC star formation histories, they found a clear transition in the dominant NSC formation (Figure 3). In low-mass galaxies (< 10^9 $M_\odot$), NSCs were found to be old and metal-poor and were likely formed through GC in-spiral, while in massive galaxies in-situ formation can explain their high masses, complex star formation histories and high metallicities. Interestingly, indications of both formation channels were found for intermediate-mass galaxies.

Regardless of this clear result, with only galaxies in a galaxy cluster the question arose whether this trend of NSC formation from GCs in dwarf galaxies would hold up in star-forming dwarfs. To address this, Fahrion et al. (2022) presented a novel sample of nine late-type dwarfs observed with MUSE. Even in this sample, the NSCs were found to be mainly old and metal-poor, and the contribution from additional *in-situ* star formation was small. This further confirmed that the NSCs in dwarf galaxies form from GCs and therefore closely resemble GCs in their properties. However, the star formation history of the galaxy imprints additional populations onto the NSC, which makes NSCs important records of past star formation episodes.

Conclusions

The MUSE instrument at the VLT has changed how spectroscopic studies of star clusters can be conducted. This is seen beyond the works mentioned in this article, as similar approaches have been used, for example, to study planetary nebulae in the central regions of galaxies (for example, Spriggs et al., 2021) or to explore globular clusters in dwarf galaxies (for example, Müller et al., 2020). Moreover, recent work has employed methods similar to those described here to analyse a larger sample of nucleated galaxies (Lyu et al., 2024), further confirming the trend with galaxy mass.

Nevertheless, unanswered questions remain. For example, it is unclear when NSCs and the observed trends in their formation pathways are established. Are the NSCs we see today already formed from then proto-GCs at high redshift? Or do the GCs form first and then merge in the later evolution? To answer these questions, the fraction of galaxies with a nuclear star cluster at higher redshift would be needed, but no such observations have yet been made. Additionally, it is unclear why some galaxies have GCs but no NSC. The lack of NSCs in high-mass galaxies might be explained by interactions with supermassive black holes (SMBHs), but the dynamical friction timescales are so short in dwarfs that NSCs formed through GCs should be ubiquitous. Perhaps galaxy interactions or the underlying dark matter profile might hinder such an in-spiral, but conclusive results even for individual systems are still missing (for example, Meadows et al., 2020). Another avenue is to couple detailed orbit-based dynamical models of galaxy nuclei with stellar population parameters. Looking into the orbital distribution of NSCs can give us important hints about the evolutionary history of the galaxy nucleus. In turn, this can enlighten us about whether the scaling relations between galaxy nuclei and host galaxy properties are driven by physical processes, like AGN feedback, or statistical ones, involving many subsequent mergers of galaxies and their NSCs and/or SMBHs.

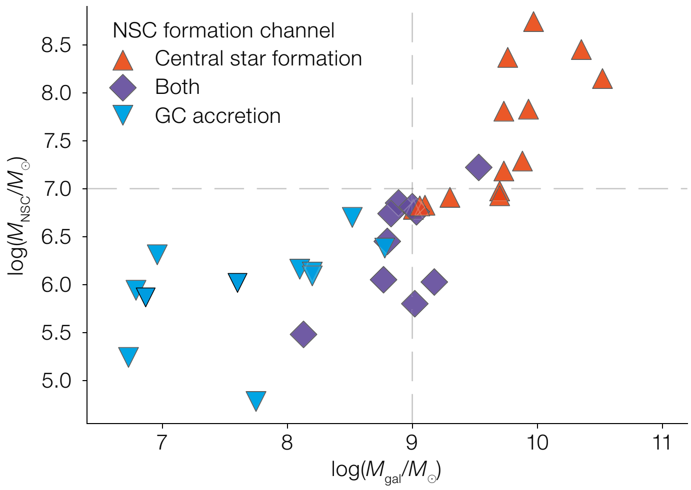

Figure 3. Dominant NSC formation channel as function of galaxy and NSC mass. Dwarf galaxies form their NSCs predominantly through the accretion of GCs, while the massive NSCs in massive galaxies form most of their mass through central star formation.

Acknowledgements

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This image shows a pair of overlapping spiral galaxies, NGC 3314a and b, in the top left, caught in a majestic cosmic dance — captured by ESO's VLT Survey Telescope (VST).

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Young Stars Discovered in Dwarf Spheroidal Galaxies Confirm their Recent Infall into the Milky Way

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Recent observations from ESA's Gaia satellite and with ESO's Very Large Telescope have identified the presence of a population of young stars, 0.5 to 2 Gyr old, in the halo of, and in dwarf spheroidal galaxies surrounding, the Milky Way (MW). It suggests that MW dwarf galaxies, currently devoid of gas, had, until recent times, enough gas to sustain a burst of star formation. The recent loss of gas coincides with their arrival in the vicinity of the MW, in agreement with orbital predictions from Gaia that indicate that most dwarf galaxies reached the MW halo less than 3 Gyr years ago. This completely changes the interpretation of their dynamics, mass and dark matter content.

A recent infall of most dwarf galaxies is predicted by the hierarchical scenario

In the last 30 years, astronomers have conducted extensive observations and analyses of the stellar populations in the dwarf galaxies surrounding the Milky Way (MW) galaxy. Several dwarf galaxies were thought to be made up of only very old stars (with ages much greater than 6 Gyr) with a low concentration of elements heavier than helium. It was then deduced that these dwarf galaxies, such as the Sculptor dwarf spheroidal (dSph), had lost their gas at these remote epochs, when they became satellites of our Galaxy, orbiting around it ever since. This scenario has a major consequence in near-field cosmology: these dwarf galaxies must have a huge quantity of dark matter in order to protect their stellar content from the disruptive force of the MW's gravitational field. Indeed, in the absence of a large amount of dark matter, tidal forces from the MW would disperse the stars of the dwarf galaxy in just a few Gyr. Until now, they have been considered as the most dark-matter-dominated galaxies in the Universe, whose total masses, derived from their large velocity dispersions, are 10 to 1000 times larger than their stellar masses.

Gaia observations (the second and third data releases, DR2 & DR3) provided detailed orbital motions for 156 globular clusters (GCs; Vasiliev, 2019), and for 46 MW dwarf galaxies (Li et al., 2021), allowing their orbital (or binding) energies to be accurately calculated. Several studies (Kruijssen et al., 2019, 2020; Massari, Koppelman & Helmi, 2019; Malhan et al., 2022) showed that several GCs are associated with the important accretion events that occurred in the MW, namely the elaboration of the bulge (12–13 Gyr ago), the Kraken (11–12 Gyr ago) and the

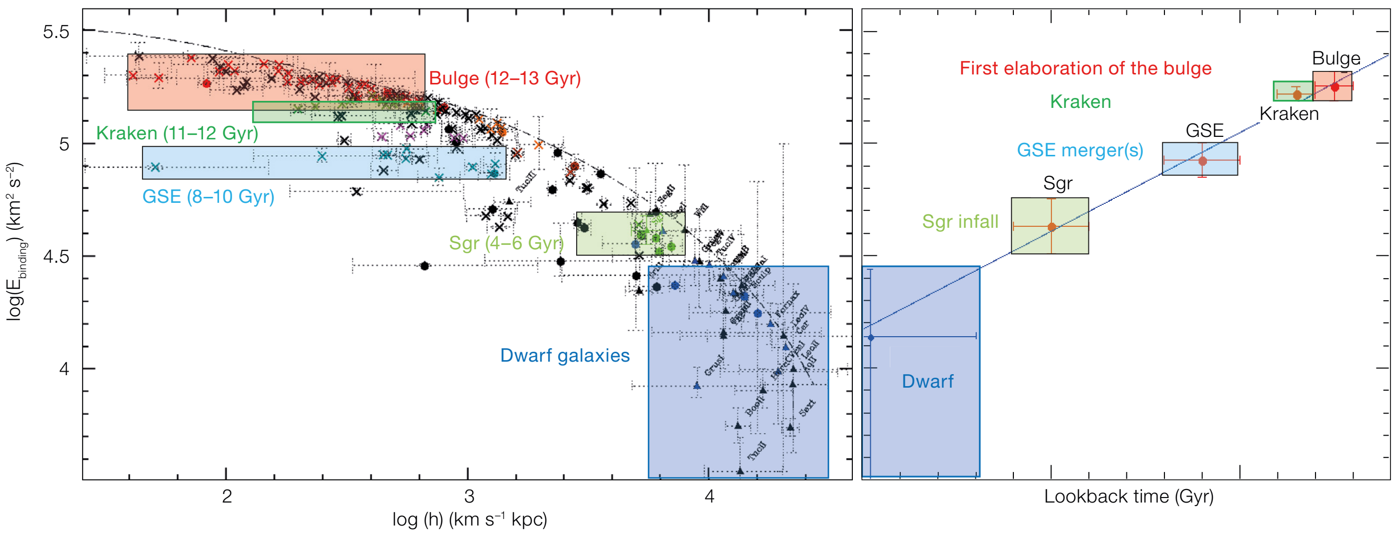
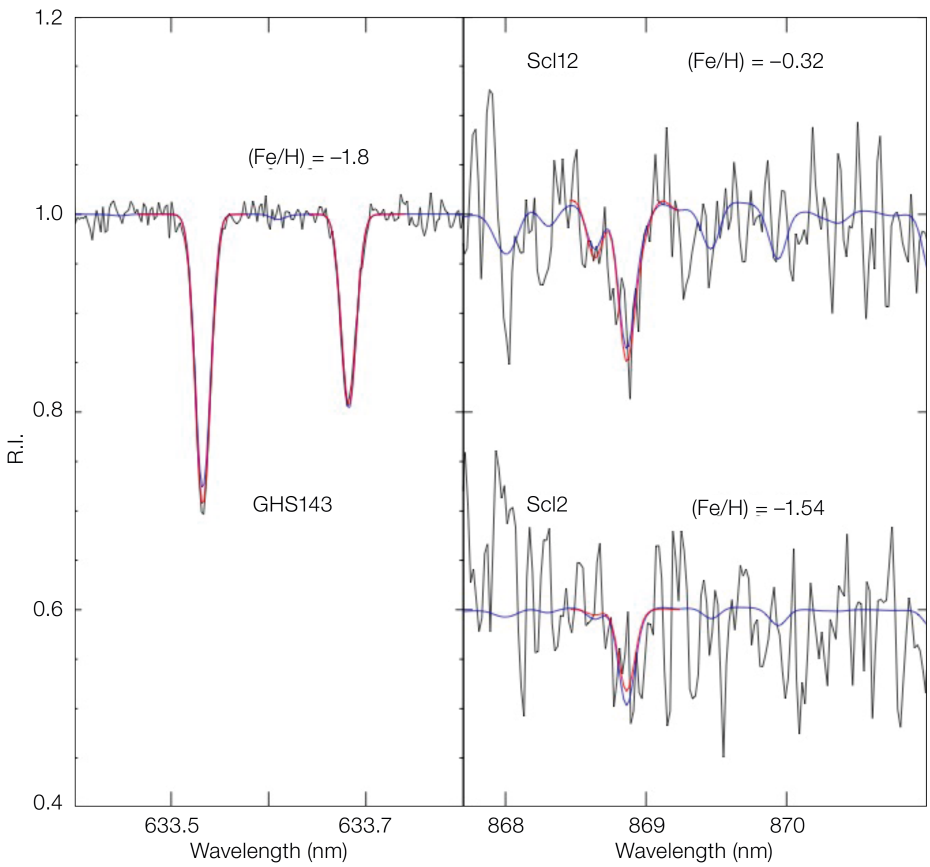


Figure 1. The left panel shows total energy versus angular momentum ($h = R_{GC} \times V_{tan}$) on a logarithmic scale, for high-surface-brightness GC (crosses), low-surface-brightness GC (filled circles), and dwarf galaxies (triangles). Structures identified by Malhan et al. (2022) and Kruijssen et al. (2020) are added in different colours. VPOS (Vast POlar Structure; see Pawlowski, Pflamm-Altenburg & Kroupa, 2012 and Li et al., 2021) dwarf galaxies are shown in blue. The dot-dashed line shows the limit that cannot be passed by any orbits, as it is fixed for a circular orbit (the largest possible binding energy for a given angular momentum). The right panel shows the corresponding lookback time of stellar system entry in the Milky Way halo as a function of its current binding energy for different families of GCs, and for the dwarf galaxies that do not belong to the tightly bound Sgr system (that is, excluding Sgr, Segue I, II, Tucana III, IV and Willman I). The blue solid line is a linear fit. A simple interpretation is that dwarf satellites with log($E_{binding}$/(km^2 s^{-2})) < 4.34 are on their initial approach (see blue box), a value close to the logarithm of the average energy (4.14 km^2 s^{-2}) of dwarf galaxies, whose scatter provides an upper limit of $E_{binding}$ = 4.34. The latter combined with the linear fit suggests a lookback time of halo entry of dwarf galaxies less than 3 Gyr.

Figure 2. Left: UVES spectrum of the young metal-poor star GHS143, for which the two Fe I lines indicate a low-metallicity star. The blue line is the synthetic spectrum corresponding to the average metallicity and the red line is the best fit to each line. The high proper motions imply that the star is unbound and falling into the Galaxy, its estimated age being between 5 and 9 Myr. Right: GIRAFFE spectra of two young stars in Sculptor, for which the 868.86 nm Fe I line indicates a difference of over 1 dex in iron abundance. The spectrum of Scl12 has been arbitrarily shifted by –0.4, for display purposes. The blue line is the synthetic spectrum corresponding to the average metallicity, while the red line is the best fit to the line.



Gaia-Sausage-Enceladus (GSE, 8–10 Gyr ago) merger events, and more recently the dwarf Sagittarius galaxy (Sgr, 4–6 Gyr ago) infall into the Galactic halo. These associations have been determined after comparing GC ages, metallicities and the orientation of their orbital angular momenta and binding energy to those of stars from which the above events have been identified. They are expected since stars and GCs are often formed together through gas-rich major-merger events (De Lucia et al., 2024; Valenzuela et al., 2024).

Figure 1 shows the distribution of GCs (crosses for the high-surface-brightness examples, large dots for the low-surface-brightness ones; see Hammer et al., 2021) and of dwarf galaxies (triangles) in the binding energy–angular momentum plane. GCs are coloured on the basis of the structures to which they belong. Each structure (bulge, Kraken, GSE, and Sgr) shows a very narrow range in binding energy, which allows them to be identified in the relation between binding energy and infall lookback time.

Galaxies like the MW follow a hierarchical structure formation, in which smaller galaxies merge into larger systems over time. This 'inside-out' growth pattern means that older structures are tightly bound to the galaxy, while more recent arrivals are less so. Hammer et al. (2023) derived the MW's accretion history (see Figure 1), which can be fitted by a single line from bulge elaboration to Sgr. The line slope is in agreement with predictions from high-resolution cosmological simulations (Rocha, Peter & Bullock, 2012; and see a detailed comparison to simulations in Hammer et al., 2024a). By extrapolating the line to the lower binding energy of dwarf galaxies, it suggests that most of the latter galaxies have reached the MW halo less than 3 Gyr ago.

Discovery of young stars in the halo and then in dSph galaxies

Thanks to the proper motions provided by Gaia, Bonifacio et al. (2024) and Caffau et al. (2024a,b) identified several stars in the MW halo with high velocities with respect to the Sun (> 500 km s^{-1}). 10 of these high-velocity stars show large masses (in excess of 1.3 $M_\odot$, half of them in excess of 2 $M_\odot$), young ages (0.3 to 2.5 Gyr old) and metallicities from –1.3 to –2.2. Figure 2 shows the Ultraviolet and Visual Echelle Spectrograph (UVES) spectrum of GHS 143 with a mass of 2.3 $M_\odot$. Measurements of metallicity from spectroscopy combined with accurate Gaia photometry allow an accurate determination of the star's mass and age[a]. It is well known that some stars may 'rejuvenate' by mass transfer from a binary companion or even by merging with another star; such a rejuvenated star is called a blue straggler, because of its anomalous position in the colour–magnitude diagram. However, the formation of blue stragglers with masses larger than two solar masses is unlikely because most halo stars are > 8 Gyr old, for which the maximum mass at the turn-off is expected to be 0.9 $M_\odot$. To explain young and massive halo stars through the blue straggler channel would require mergers involving three stars, which are extremely rare events. The simplest explanation of the data is that these stars are not rejuvenated, but are genuinely young.

The origin of these halo young stars is a puzzle, since the halo does not contain large amounts of gas to fuel star formation. It is thus likely that they are formed during the earlier infall of a dwarf galaxy, for which the original gas content has been ram-pressurised during its interaction with the Galactic corona. It has prompted us to verify whether or not there might be also a population of young stars in the most massive dwarfs, i.e., dSph galaxies. Yang et al. (2024) have

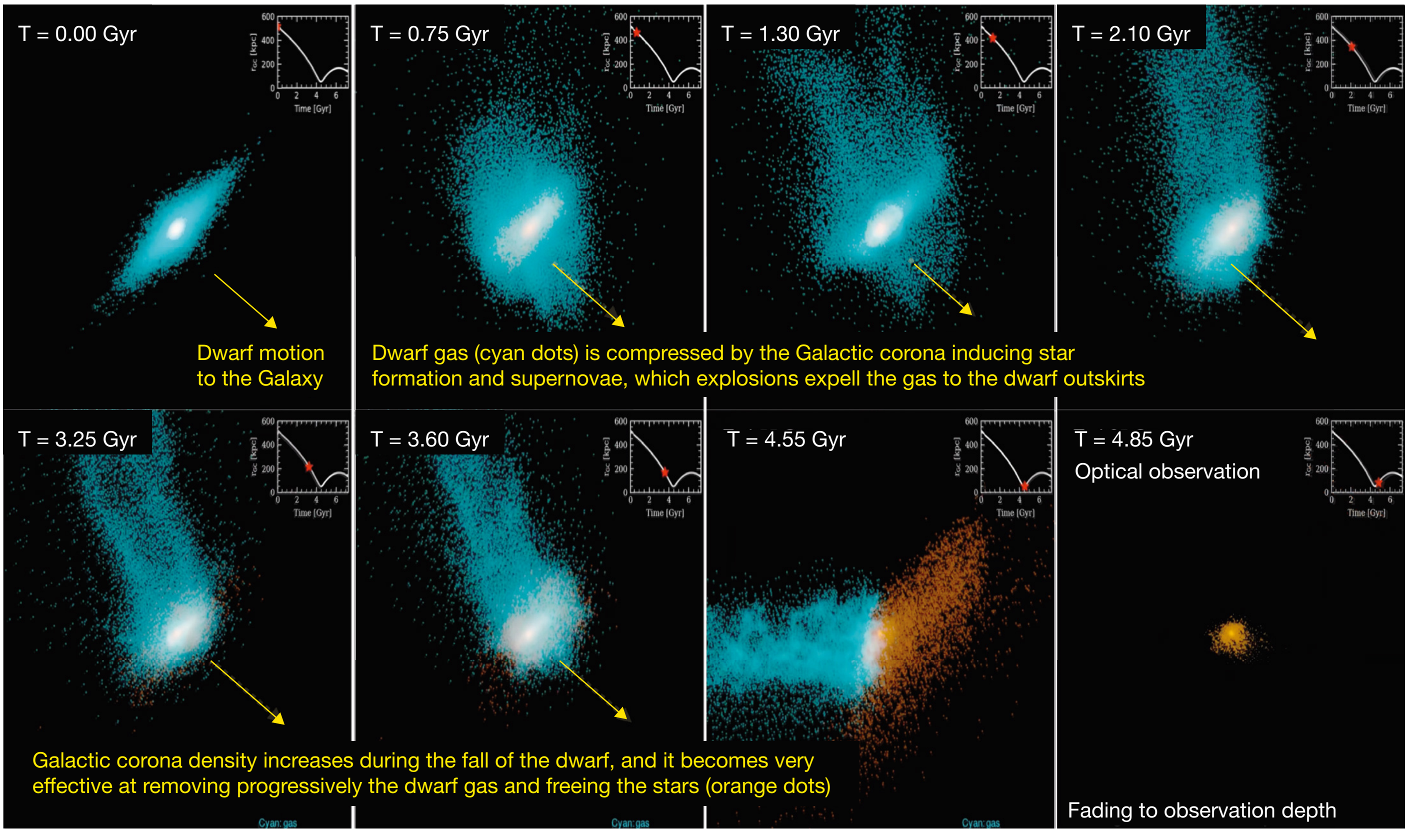


Figure 3. Snapshots of a video summarising the hydrodynamical simulation of the infall of a gas-rich dwarf galaxy that is ram-pressurised during its infall into the MW corona (Wang et al., 2024). Gas is represented by cyan particles and stars by red particles. The yellow arrow indicates the dwarf motion, and the insert on the top-left the radial evolution with time. The final galaxy in the bottom-right panel has properties very similar to the Sculptor dSph.

been able to 'filter' the dSph members by excluding the foreground stars (from the MW) that appear in the field of view of the dSph galaxies. This filtering is extremely efficient, and was not possible before the availability of the Gaia data. For example, in the field of view of Sculptor, half of the stars are foreground, but thanks to the filtering using the Gaia proper motions, this contamination is at most 1.4%! This filtering method allowed the unambiguous identification of young stars in Sculptor whose ages are between 0.5 and 2 Gyr and whose masses are up to three times that of the Sun, after determining their metallicities through observations with the GIRAFFE spectrograph (see Figure 2). Besides confirming that these stars belong to Sculptor, spectroscopic observations allow their masses to be derived. Because the turnoff (TO) point of the Sculptor dSph is similar to that of the halo (0.9 $M_{\odot}$), it is also unlikely that Sculptor young stars can be blue stragglers. Besides Sculptor, three additional dSphs, Sextans, Ursa Minor and Draco, show the presence of a young star population, demonstrating that the phenomenon is fairly common, especially because other dSphs (Fornax, Carina, Leo I and Leo II) are also known to contain young populations. The most favourable location in the colour-magnitude diagram to identify young stars is the so-called 'yellow plume' (see, for example, Gullieuszik et al., 2008), an almost vertical sequence to the blue of the red giant branch. These stars are three to four magnitudes brighter than the TO and are young evolved stars in the core helium-burning phase, or young sub-giant stars. The same region can also be occupied by evolved blue stragglers, but such an interpretation becomes unlikely for stars of mass above two solar masses.

Conclusions

The discovery of young stars in four dSph galaxies formerly considered as uniquely made of old stars changes our view of the history of their motions relative to the MW. It supports the scenario of a recent infall suggested by the precise determination of their orbits from Gaia. In fact, since stars are known to form within gas clouds, the dwarf galaxies must have contained sizable amounts of gas up to 0.5 to 2 Gyr years ago. It is well accepted that MW dwarf progenitors were gas-rich galaxies similar to present-day dwarf irregular galaxies observed in the field. Once they arrived in the MW halo, their gas was stripped by the ram pressure exerted by the hot gas in the MW corona. The process is quite rapid, because masses of dwarf galaxies are three to five orders of magnitude smaller than that of our galaxy.

The above discoveries have considerable consequences for our understanding of the nature of dwarfs surrounding the MW. Hydrodynamical simulations (Wang et al., 2024) show that during the interaction with the MW corona gas, the stellar content is considerably shaken by turbulence effects during the process (see Figure 3[b]). dSph progenitors gradually lost their gas, provoking a strong disequilibrium in the residual stellar content, including by tidal shocks exerted by the MW's gravity (Hammer et al., 2024b). When the gas is fully lost, stars begin to expand thanks to the associated loss of internal gravity, and this naturally explains the presence of stars associated with many dwarfs while being very far from their centres (Chiti et al., 2023; Sestito et al., 2023; Longeard et al., 2022; Waller et al., 2023). Hydrodynamical simulations predict that, in the case of a recent arrival, a small number of stars must be formed during the interaction between the gas-rich progenitor and the MW corona, which is consistent with the observed number of young stars (Yang et al., 2024). They also reproduce all the properties of dwarf galaxies, including their observed velocity dispersions, with a very limited amount of dark matter, or even without dark matter at all.

Our results are suggestive and require further confirmation. In particular spectroscopic observations at higher signal-to-noise ratio of more yellow plume stars in Sculptor and other dwarf galaxies are needed. Young stars with masses in excess of two solar masses have rotational velocities in excess of 200 km s^{-1} when on the main sequence. As they evolve they slow down, but they can still show measurable rotational velocities of the order of 10–20 km s^{-1} (Lombardo et al. 2021). Evolved blue stragglers, instead, can spin up to 100 km s^{-1} at the time of mass transfer, but spin down rapidly, even more so as they evolve. At the same time we need to obtain high-resolution, high-signal-to-noise spectra for the many halo yellow-plume stars, that we can select from Gaia. Their metallicity and dynamics should trace their origin to an existing or disrupted dwarf galaxy.

If confirmed, this novel paradigm for explaining the observations of MW dwarf galaxies will become a serious contender to the scenario of dark matter-dominated MW dwarf galaxies, and this could lead us into a new area in near-field cosmology.

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Notes

[a] Determination of metallicity through spectroscopy allows the appropriate isochrones in the colour–magnitude diagram to be chosen, and hence the stars' ages and masses to be estimated.

[b] A video of the simulation of the Sculptor dSph (Wang et al., 2024) shown in Figure 3 can be seen at https://www.youtube.com/watch?v=SwxSdmfQis4

B. Haeussler/ESO

In this portrait of ESO's Paranal Observatory, taken in early February, our planets appear to parade one after the other across the night sky. In addition to the Moon, our own Milky Way, and the comet C/2024 G3, we can see Saturn, Venus, Jupiter and Mars — even Neptune and Uranus are hiding here too! Often on nights with a few planets in view, you can draw an imaginary straight line in the night sky through them. This is due to their orbital paths being relatively aligned along a single, flat plane called the ecliptic. (In reality, the planets aren't aligned one after the other in a straight line in the Solar System, they are fanned out; but we can still see them simultaneously in the sky, which only happens every few years.) You may notice that in this image the planets are not contained within the band of the Milky Way, and that the line that connects them crosses the Milky Way at an angle. This is due to the ecliptic being tilted at about 60 degrees to the galactic plane on which our entire Milky Way lies. If the Milky Way could somehow be shrunk down to lie flat on a table, our Solar System would be jutting out like a pin stuck in it at an odd angle.

Telescopes and Instrumentation

This impressive image of comet C/2024 G3 (ATLAS) was captured on 29 January from ESO's Paranal Observatory by Abel de Burgos Sierra, an ESO Fellow in Chile. Gas and dust particles are ejected from the nucleus and pushed away from the Sun by the solar wind and radiation, creating a spectacular display with multiple tails.

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NIRPS Joins HARPS: Setting New Standards at Infrared Wavelengths

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The Near-InfraRed Planet Searcher (NIRPS) is a high-resolution, near-infrared spectrograph optimised for detecting and characterising exoplanets around low-mass stars, working in tandem with the High Accuracy Radial velocity Planet Searcher (HARPS). While HARPS set new standards 20 years ago with its metre-per-second-level precision, NIRPS follows this successful path, achieving even better precision at infrared wavelengths. This article presents an overview of the design of NIRPS, its on-sky performance, its Guaranteed Time Observation programme, and its first scientific results.

Introduction

The discovery of the first exoplanet orbiting a solar-type star (Mayor and Queloz, 1995), and of the first transiting exoplanet (Charbonneau et al., 2000), stand as pivotal moments in astrophysics. The quest for nearby habitable worlds and evidence of biological activity beyond the Solar System has prompted the construction of powerful observatories such as Kepler (Koch et al., 2010), the Transiting Exoplanet Survey Satellite (TESS; Ricker et al., 2015), the James Webb Space Telescope (JWST; Gardner et al., 2023) and, very soon, ESO's Extremely Large Telescope (ELT; de Zeeuw, Tamai & Liske, 2014).

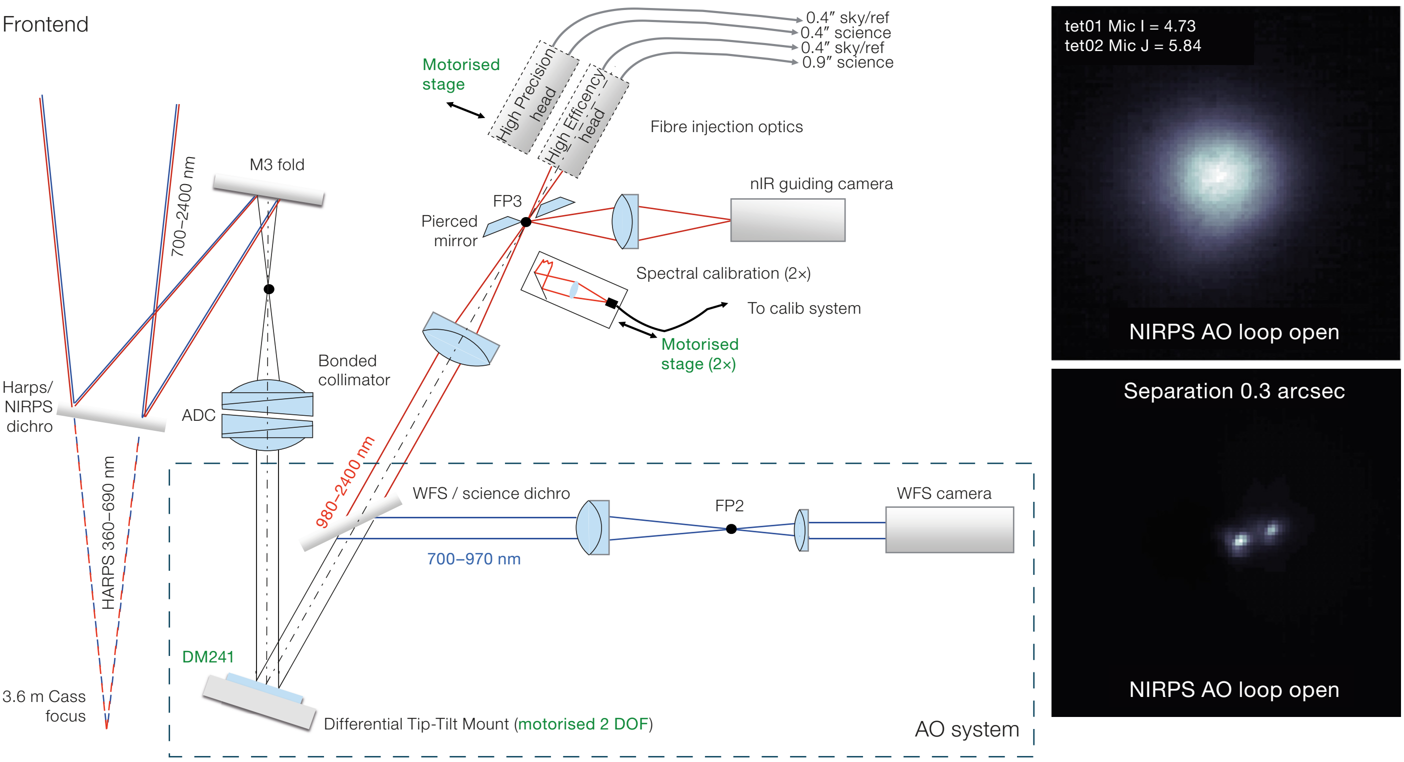

Figure 1. Left: schematic of the NIRPS frontend. Right: images from the guiding camera of a binary star (0.3 arcseconds separation) with the AO loop open (top) and closed (bottom). From Bouchy et al. (2025).

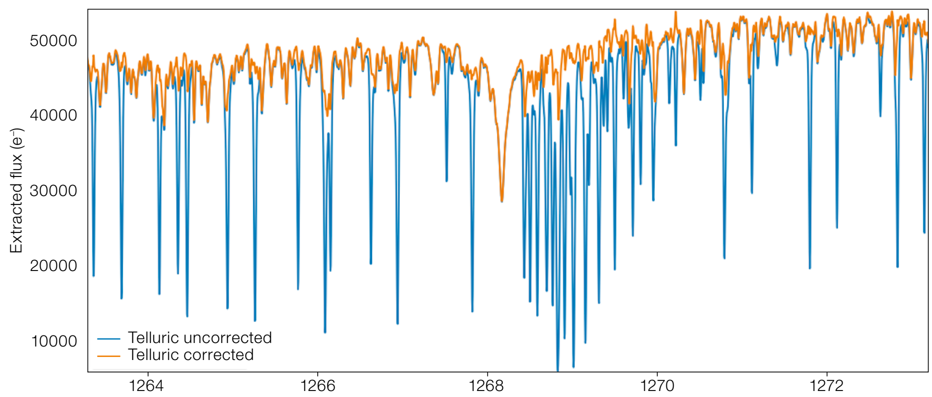

Figure 2. Extracted and wavelength-calibrated spectrum of Proxima Cen in HE mode, centered at 1268 nm. Blue: uncorrected spectrum; orange: telluric-corrected spectrum. From Bouchy et al. (2025).

The rapid progress in exoplanet research over recent decades was driven largely by precision velocimetry and in particular the development of fibre-fed optical spectrographs like the High Accuracy Radial velocity Planet Searcher (HARPS; Mayor et al., 2003), which set new standards by achieving metre-per-second precision. Advances in large-format infrared detectors, largely motivated by and developed for JWST, paved the way for a new generation of precision infrared spectrographs tailored to studying low-mass stars. This context prompted the Universities of Montreal and Geneva, in collaboration with the Institute of Astrophysics and Space Science (Portugal), the Canaries Institute of Astrophysics (Spain), Grenoble Alpes University (France), the Federal University of Rio Grande do Norte (Brazil), and ESO, to initiate the development of an 'infrared HARPS' for the southern hemisphere.

Low-mass M dwarfs, which dominate the Milky Way's stellar population (Reylé et al., 2021), are excellent targets for exoplanet studies. Their small radii and masses amplify detection signals via radial velocity (RV) and transit methods, while their low luminosity means that habitable zones lie closer to the star, with orbital periods measured in weeks rather than a year, greatly simplifying the characterisation of potentially habitable exoplanets.

The near-infrared (NIR) is particularly suited to M dwarf studies, as it mitigates stellar activity jitter on RV measurements compared to the optical and provides access to helium and molecular signatures like H_2O, O_2, CO, CH_4, and CO_2, critical for atmospheric studies. These advantages have driven the development of high-resolution NIR spectrographs, including GIANO (Oliva et al., 2012), the Habitable-zone Planet Finder (HPF; Mahadevan et al., 2012), the Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs (CARMENES; Quirrenbach et al., 2014), the InfraRed Doppler (IRD) instrument (Kotani et al., 2018), and SpectroPolarimètre InfraRouge (SPIRou; Donati et al., 2020).

The Near-InfraRed Planet Searcher (NIRPS), the newest addition to this suite, builds on the legacy of HARPS (Mayor et al., 2003) and the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO; Pepe et al., 2021), while leveraging the infrared expertise and experience gained from SPIRou. Operating in tandem with HARPS, NIRPS provides an unparalleled optical-NIR capability for precision velocimetry. This dual-wavelength approach enhances the precision of RV measurements and significantly improves our ability to disentangle planetary signals from stellar jitter noise. This article presents a brief overview of NIRPS, including its design, on-sky performance, initial results, and highlights from its extensive Guaranteed Time Observation (GTO) programme. For a more comprehensive description of NIRPS, readers are referred to Bouchy et al. (2025).

NIRPS+HARPS: a unique dual optical-infrared precision velocimeter

NIRPS is a fibre-fed, highly-stabilised echelle spectrograph operating in the NIR and installed on the ESO 3.6-metre telescope at La Silla, Chile. The instrument includes a frontend bonnette at the Cassegrain focus, linked via optical fibres to the cryogenic spectrograph in the coudé room. The frontend integrates an adaptive optics (AO) system to enhance efficiency and minimise the instrument's size. As for HARPS, NIRPS's spectrograph is housed in a thermally-controlled enclosure to ensure optimal thermal stability.

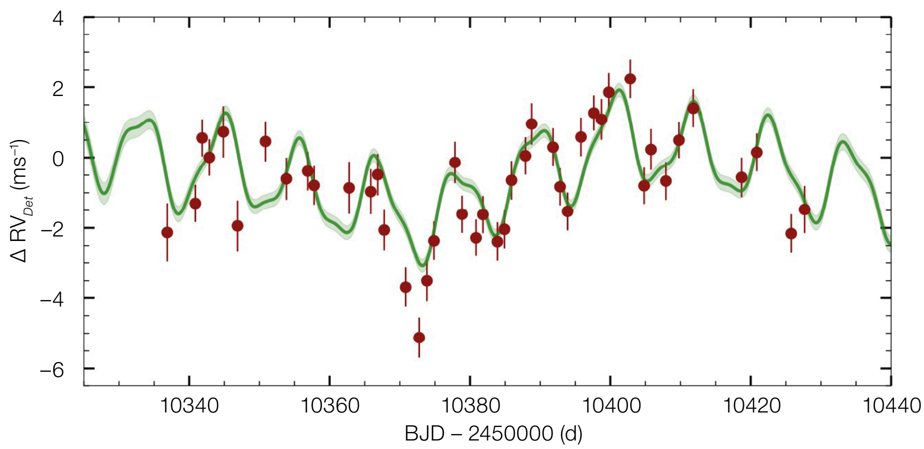

Figure 3. High cadence of NIRPS RV detrended data of Proxima Cen, along with the best model fit, showing residuals with an RMS of 81 cm s^{-1}. From Suárez Mascareño et al. (2025).

NIRPS operates in the *Y*, *J*, and *H* bands, covering a wavelength range from 972.4 nm to 1919.6 nm. It offers two fibre sizes (0.4 and 0.9 arcseconds) yielding resolving powers of *R* = 90 000 for the high-accuracy (HA) mode and *R* = 75 000 for the high-efficiency (HE) mode. This spectral range enables the detection of molecular signatures such as water and methane in planetary atmospheres. The frontend module (Figure 1) houses the AO system, which corrects for atmospheric turbulence to improve light coupling into the fibres under variable seeing conditions. A dichroic beam splitter simultaneously directs light to both HARPS and NIRPS, enabling parallel optical and NIR observations.

The fibre link transports light to the spectrograph and incorporates a fibre stretcher and double scrambler to reduce modal noise that impacts radial velocity (RV) measurements. The calibration unit includes hollow-cathode (HC) uranium-neon lamps and a Fabry-Pérot (FP) étalon to illuminate a reference fibre alongside the science fibre. The HC provides absolute wavelength calibration, while the FP allows drift correction. Calibrations are performed daily, with a laser frequency comb currently under commissioning.

The backend spectrograph is housed within a vacuum vessel, with its optical bench stabilized to 75 K, maintaining thermal variations within 0.1 mK. The optical design features a reflective double-pass collimator, a 13-lines mm^{-1} R4 echelle grating, a carousel of five ZnSe prisms for cross-dispersion, and a refractive camera that feeds a 4096 × 4096-pixel Hawaii-4RG (H4RG) infrared detector with 15-µm pixels. The full wavelength range spans 71 orders, with the line spread function sampled by three pixels.

Data pipeline

The NIRPS data reduction pipeline (NIRPS-DRS) is adapted from the ESPRESSO pipeline, incorporating features inspired by the APERO pipeline (Cook et al., 2022), a versatile framework initially developed for SPIRou. While NIRPS-DRS and APERO share similarities, they differ in key aspects, such as their approaches to telluric correction (see Bouchy et al., 2025). The two independent pipelines are particularly valuable for cross-validation and assessing the robustness of scientific results.

The pipeline begins with order localisation, flat-fielding, and wavelength calibration. The FP etalon ensures precise drift monitoring when necessary[a], while uranium-neon lamps, combined with FP frames, provide an estimate of the FP cavity length, forming the basis for the absolute calibration across nights and observing runs. A major challenge in NIR precision velocimetry is the contamination of stellar spectra by telluric absorption lines. The NIRPS-DRS pipeline includes a telluric subtraction module developed for

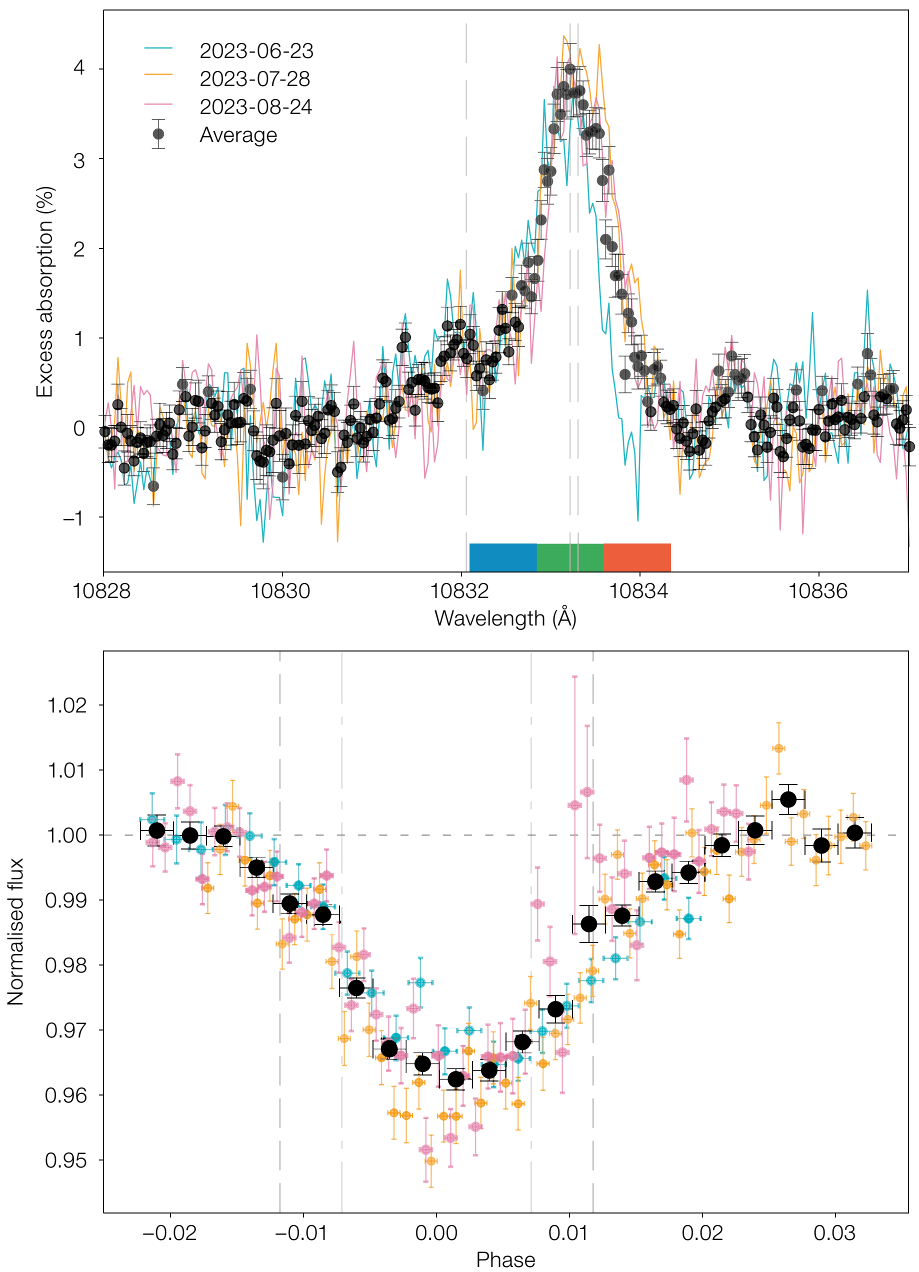

Figure 4. Transmission spectra (top) and excess helium light curves (bottom) comparison between transits (in cyan, orange, and rose) and the average in black. On the top panel, three spectral regions (blue, green, and red) are identified to measure the temporal variation of the helium signature. From Allart et al. (2025).

ESPRESSO (Allart et al., 2022), while APERO is using an ensemble of telluric standards, fast-rotating early-type stars, and a principal component analysis (PCA)-based method for modelling and removing telluric lines. Figure 2 displays a portion of the *J*-band spectrum of Proxima Cen, both before and after telluric correction, demonstrating the effectiveness of our method, which is absolutely crucial for achieving metre-per-second-level precision at infrared wavelengths.

Radial velocity extraction is performed using two complementary methods: the standard cross-correlation function (CCF) technique and the line-by-line (LBL) method (Artigau et al., 2022). The CCF provides immediate RV measurements for each observation, while the LBL method, which constructs a template spectrum from a time series, generally delivers more precise RVs with less sensitivity to outliers, achieving, for example, a twofold improvement on the ESPRESSO uncertainties for the temperate super-Earth LHS 1140b (Cadieux et al., 2024).

On-sky performance and first results

NIRPS commissioning took place over two years from November 2019 to March 2023 with the official first light on 17 May 2022. The commissioning phase of NIRPS demonstrated excellent performance, meeting or exceeding its design requirements.

The instrument's overall throughput peaks at 13% in the *H* band. The AO system significantly improves fibre coupling efficiency, achieving typical encircled energy of 55% and 70% for the HA and HE modes, respectively; this performance is constant up to $I = 11$. Modal noise is mitigated through the fibre stretcher and through AO scanning by using the tip/tilt mirror to move the star within the fibre core randomly during an exposure. Together, both stretching and AO-scanning yield a modal noise reduction by a factor of five for the HE mode, leaving a residual noise of 0.43% (SNR~230) similar to the flat-field stability of 0.65% which translates into RV noise of 0.9 m s^{-1}. The AO was successfully tested to lock onto small (< 2-arcsecond) Solar System objects, such as Saturn's and Jupiter's moons.

RV performance was characterised on several RV standards with known planetary systems such as Proxima Cen, featuring two planets including an Earth-mass one in the habitable zone (Proxima b). As shown in Figure 3, Proxima b is clearly detected with a residual noise of ~80 cm s^{-1} compared to 2.5 m s^{-1} from the HARPS data alone. NIRPS is the first NIR velocimeter to demonstrate sub-metre-per-second performance, partly due to the excellent sub-Kelvin thermal stability of the spectrograph yielding typical drifts of 3–4 cm s^{-1} day^{-1} and wavelength uncertainties at the level of 50–70 cm s^{-1}.

High-resolution spectroscopy is a powerful tool for probing exoplanetary atmospheres via transmission spectroscopy and constraining orbital architecture, including the spin-orbit angle, through the Rossiter–McLaughlin (RM) effect. This capability was demonstrated by observing three transit events of the warm Saturn WASP-69b. As shown in Figure 4, NIRPS successfully detected the helium triplet near 1083 nm in the planet's atmosphere, with evidence of variability indicative of cometary-like tail mass loss. The RM measurements suggest a slightly misaligned orbit.

NIRPS Guaranteed Time Observation programme highlights

In exchange for building and operating the instrument, ESO awarded the NIRPS consortium 725 nights over five years. These are allocated to three core science programmes, each receiving 225 nights, with an additional 50 nights reserved for 'other science' programmes.

Blind RV search for exoplanets orbiting nearby low-mass stars

This core sub-programme is primarily dedicated to a blind search for planets around M dwarfs (< 0.6 $M_\odot$) with three major objectives: (1) identifying the nearest exoplanetary systems amenable to atmospheric characterisation in reflected light with the ELT (Snellen et al., 2015; Pallé et al., 2023) and which are orbiting M dwarfs within approximately 6 pc; (2) searching for exoplanets around nearby ultra-cool dwarfs to estimate how frequently planet formation occurs around such stars with masses below 0.1 $M_\odot$; and (3) understanding the process of planet formation and dynamical evolution by searching for planets around young, very low-mass stars.

Mass characterisation of transiting planets orbiting M dwarfs

This programme is dedicated to providing mass measurements of transiting exoplanets unveiled by TESS and other transit surveys through various sub-programmes. Mass measurements are essential for interpreting transmission spectra obtained with JWST and constraining internal structure models. This programme aims to shed light on the nature, formation and evolution of super-Earths and mini-Neptunes. One sub-programme is dedicated to precise (~10%) mass measurements of small rocky planets to constrain their core mass fraction.

High-resolution spectroscopy of exoplanet atmospheres

The third core programme centres on atmospheric studies of exoplanets, primarily hot gas giants, using transmission and emission spectroscopy. Its objective is to uncover the chemistry, dynamics, and orbital architectures of exoplanet atmospheres. The programme combines a broad atmospheric reconnaissance survey with in-depth analyses of a carefully selected sample of exoplanets, aiming to establish critical reference datasets in preparation for the upcoming ELT era.

Other science

HARPS and NIRPS provide a unique capability, each performing at the metre-per-second level, for stellar activity studies as well as stellar characterisation, including abundance determination (for example, Jahandar et al., 2025), in particular refractory elements (Fe, Mg, Si) which are critical inputs for internal structure modelling. This approach was applied to LHS 1140 using commissioning data, revealing that the temperate super-Earth LHS 1140b is likely a water world with a 10–20% water mass fraction (Cadieux et al., 2024).

Solar observations

The HARPS Experiment for Light Integrated Over the Sun (HELIOS) solar telescope (Dumusque et al., 2015) feeds both HARPS and NIRPS, and continuously monitors the Sun as a star. High-cadence solar spectra enable detailed insight into solar variability and its effect on disc-integrated radial velocity and on the retrieval of planetary atmospheric parameters (Mercier et al., 2025).

Summary

NIRPS represents a major milestone in precision infrared velocimetry, achieving sub-metre-per-second precision through advanced telluric subtraction techniques and post-processing algorithms like LBL. Early results demonstrate its considerable potential for precise mass determination, exoplanet atmospheric characterisation, and stellar studies, including activity analysis and abundance measurements.

With its exceptional performance and ambitious GTO programme, NIRPS is poised to play a central role in exoplanet research. NIRPS lays the foundation and expertise needed for the ELT era, where high-resolution infrared spectroscopy will be essential for characterising the atmospheres of nearby exoplanets through reflected light.

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Notes

[a] In practice, NIRPS is so stable that the FP is not used during science observations.

ESO/Digitized Sky Survey 2. Acknowledgment: Davide De Martin

This image shows the RCW 38 star cluster in visible light. Dust absorbs most light at these wavelengths, hiding large areas of this cluster from us.

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Optimisation of the SPHERE Adaptive Optics Setup at ~11 mag

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We have extended the recent analysis of the SPHERE adaptive optics (AO) performance for faint stars. In particular, we compared the raw contrast reached using the medium-frequency (600 Hz) and low-frequency (300 Hz) modes on different targets with G > 11 mag, and under different atmospheric conditions. We found that using the medium-frequency mode in this magnitude range leads to significantly better contrast. Based on these results, we have updated the AO frequency setup accordingly, that is, we extended the 600 Hz mode by one magnitude, up to 11.5 mag.

Introduction

The Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE; Beuzit et al., 2019) is a high-contrast imaging facility that is equipped with a powerful adaptive optics (AO) system, called SAXO (Fusco et al., 2006). The instrument comprises three different subsystems: the Zurich imaging polarimeter (ZIMPOL), which is sensitive to visible light; the InfraRed Dual-band Imager and Spectrograph (IRDIS) and the integral field spectrograph (IFS), that are sensitive to near-IR light (*Y*, *J*, *H* and *K* bands); and SAXO, which is equipped with a visible wavefront sensor (WFS). SPHERE has proven to be efficient at detecting faint companions and protoplanetary discs, reaching a final contrast better than 15 mag (beyond ~ 300 mas), when using angular and reference differential imaging (for example, Wahhaj et al., 2021) on bright targets, and reaching a Strehl ratio greater than 90%. However, one of the main limitations of SAXO is the use of a visible WFS, whose performance is strongly degraded beyond *G* ~ 12 mag, as shown by Jones et al. (2022; hereinafter J22). This limits our ability to study stars in young stellar associations, which are intrinsically red and hence significantly fainter in the visible than in the near-IR. This problem will be addressed by the SPHERE AO system upgrade, called SPHERE+ (Bocaletti et al., 2020), which will be equipped with a pyramid WFS sensitive to IR light. Hence, before this upcoming upgrade (whose first light is foreseen for 2027), it is very important to optimise the AO setup, so that we are able to reach the best possible AO correction, pushing the SAXO limits. Motivated by this, and based on the results presented in J22, we tested different setups to optimise the AO correction and to maximise the scientific return of SPHERE data.

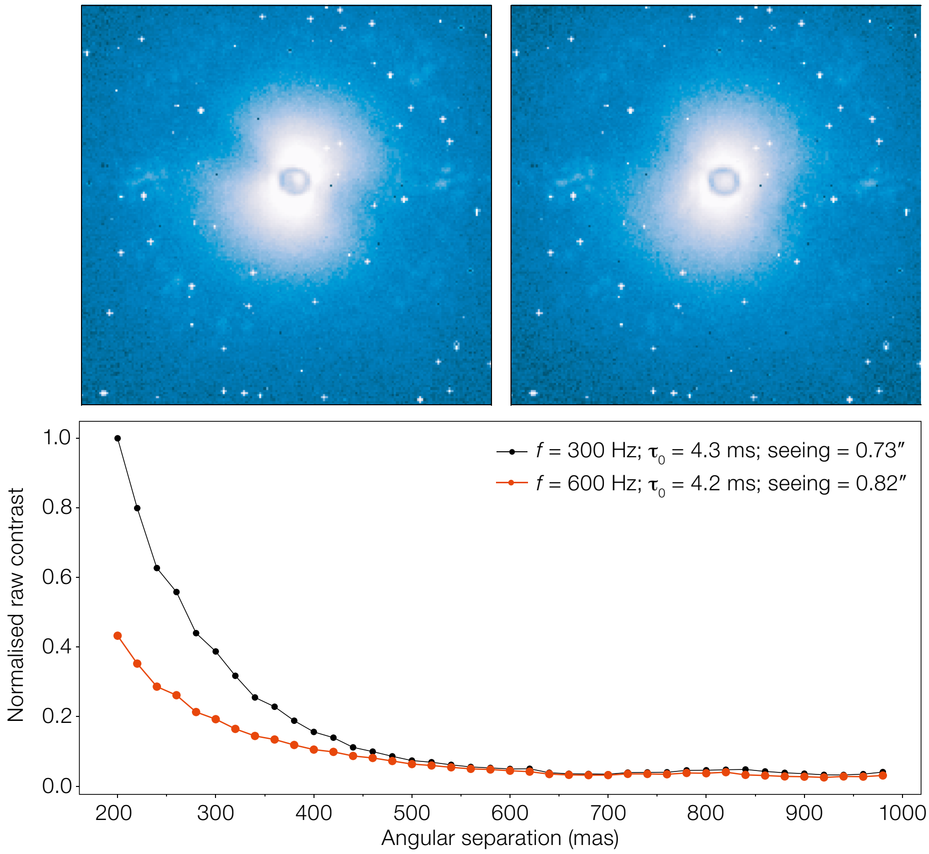

Figure 1. IRDIS coronagraphic raw images of V* NN Lup observed on 2023-06-16, using the 300 Hz and the 600 Hz modes (upper left and right image, respectively). The corresponding normalised raw contrast curves are shown below.

Observations

We observed three stars on four different nights, under different atmospheric conditions[a]. Details of the observations are summarised in Table 1. We mainly followed the methodology presented in J22, that

			300 Hz		600 Hz	
Star name	G mag	Night	τ_0 (ms)	seeing (arcsec)	τ_0 (ms)	seeing (arcsec)
V* NN Lup	11.6	2022-08-01	4.8	0.8	4.8	0.9
V* NN Lup	11.6	2023-06-16	4.4	0.5	4.5	0.5
UCAC2 18885095	11.3	2024-04-20	4.5	0.6	5.5	0.7
2MASS J13015435-4249422	11.1	2022-0731	4.5	0.8	4.7	0.8

Table 1. List of the observed stars, Gaia EDR3 *G*-band magnitude, night of observations, and mean atmospheric conditions during the observing sequence.

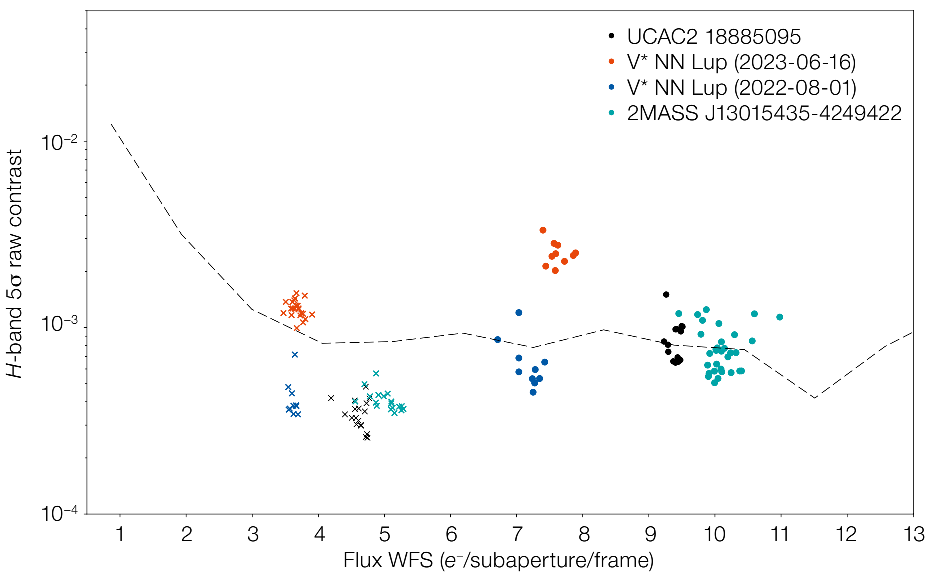

Figure 2. *H*-band raw contrast as a function of the instant flux received in the visible WFS. The dots and crosses correspond to individual frames observed with the 300 Hz and 600 Hz modes, respectively. The dashed line corresponds to the measured contrast for the 300 Hz mode, including observations taken under TCAT30 (τ_0 > 4.5 ms; seeing < 0.80 arcsec) or better atmospheric conditions (updated from Figure 3 in J22).

is, the observations were performed with IRDIS, using the H23 filter. For each star we first obtained a flux (F) sequence followed by an object (O) coronagraphic sequence. The detector integration time for each flux frame was between the minimum of 0.8 s and 8 s, and for the object frames was 32 s. We repeated the procedure using the same star, but this time changing between the low-frequency (f = 300 Hz) and the medium-frequency (f = 600 Hz) AO modes. We did this immediately after the first F–O sequence was finished, so that the airmass and atmospheric conditions were as close as possible between the two sets of observations.

Methods and results

For each individual frame in each sequence, we computed the normalised raw contrast curve, and the 5-σ raw contrast at a separation of 300 mas (see equation 1 of J22). To visualise the difference in the AO correction using these two modes, we compared individual frames and their resulting contrast curves. Figure 1 shows an example of this, for the G = 11.6 mag star V* NN Lup. The data were collected on 2023-06-16, under relatively good atmospheric conditions. The difference in the AO correction between the two different AO modes can be seen in the raw images. In particular, the effect of the wind-driven halo (see Cantalloube et al., 2020) is partially supressed with the 600 Hz mode. Moreover, the contrast curves show a significant improvement with this mode, up to a separation of about 500 mas. Finally, Figure 2 shows the raw contrast at 300 mas, as a function of the instant flux measured by the visible WFS, for the two different modes. As can be seen, there is a significant improvement (typically a factor of around two to three) in the raw contrast achieved when using the 600 Hz mode.

Summary and conclusions

Motivated by the results reported in J22, we have compared the SPHERE/IRDIS *H*-band raw contrast achieved when using the 300 Hz and 600 Hz AO frequency modes, for stars with G ~ 11 mag. For this, we performed back-to-back observations of stars in this magnitude regime, swapping between these two modes. As expected, we observed a significant improvement in the raw contrast when using the 600 Hz mode, in all four observing sequences. Based on these results, we adapted the SAXO AO setup table in August 2024, meaning that currently the faster correction mode is automatically selected up to G = 11.5 mag (in the past the limit was 10.5 mag). This was actually a relatively conservative choice, considering that we can expect a similar contrast for stars as faint as G ~ 12 mag, where the degradation of the AO correction is expected to take place (corresponding to about 3 e^- per subaperture per frame). We plan to re-adapt this limit accordingly. Finally, these tests show that for future instruments equipped with extreme AO systems, such as SPHERE+ itself, a more flexible AO frequency correction should be selected based on the instant flux on the WFS.

Acknowledgements

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Notes

[a] We excluded two stars from the analysis, since the atmospheric conditions were very unstable during the observing sequence.

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PoET: the Paranal solar ESPRESSO Telescope

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The detection and characterisation of other 'Earths', orbiting other suns, is a bold objective of present-day astrophysics. However, this quest is severely challenged by astrophysical 'noise' from the host stars, whose signatures distort the observed spectra. Motivated by this problem, we are building a dedicated facility, the Paranal solar ESPRESSO Telescope (PoET). PoET will collect solar light and channel it into the ESPRESSO spectrograph, allowing us to use the Sun as a proxy to unambiguously identify and understand the sources of relevant variability in solar-type stars.

The quest for other Earths

More than 5000 extrasolar planets have been confirmed to date. Present-day discoveries have already allowed one major conclusion: rocky planets seem to be ubiquitous around solar-type stars. Despite the impressive results, no Earth-analogue orbiting a Sun-like star has yet been unambiguously discovered and characterised, even if rocky planets around lower-mass/smaller M-dwarf stars are within reach (for example, Faria et al., 2022; Demangeon et al., 2021).

One of the main battle-horses for the detection and characterisation of exoplanets is high-resolution spectroscopy (for example, Mayor, Lovis & Santos, 2014). Doppler spectroscopy measurements, complemented with transit photometry of planets transiting bright nearby stars (Lissauer et al., 2014), are particularly relevant and allow both their mass and radius to be derived, and thus their mean density. Complementary observations and modelling allow their interior and atmospheres to be probed (for example, Ehrenreich et al., 2020).

Ground-based high-resolution spectrographs such as the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO; Pepe et al., 2021), capable of achieving radial velocity (RV) precisions down to 10 cm s^{-1} — the typical amplitude of the signal induced by an Earth-like planet orbiting a Sun-like star — represent relevant steps in this effort. ESPRESSO will be complemented by high-resolution optical and near-infrared spectrographs on ESO's Extremely Large Telescope (ELT), for example with the ArmazoNes high Dispersion Echelle Spectrograph (ANDES; Marconi et al., 2024), whose design is optimised for the detection of exoplanet atmospheres. These instruments will be key to following up Earth-like planets detected by missions such as ESA's PLAnetary Transits and Oscillations (PLATO; Rauer et al., 2024).

The stellar challenge

In this quest, the greatest challenge to overcome is related to stellar physics, or rather to the astrophysical 'noise' coming from the host stars that distorts the observed spectra.

The physical processes underlying magnetically active features (spots, faculae; for example, Shapiro et al., 2016) produce variations in the observed line profiles and positions. As activity-related features appear and disappear from the stellar disc, they induce spectral variability on timescales typical of the rotational period of the star, as well as of its long-term magnetic cycle. Amplitudes can be as high as several tens or even hundreds of metres per second in RV (for example, Meunier et al., 2017; Faria et al., 2020). Stellar granulation (Dravins, 1982) and p-mode oscillations (for example, Chaplin & Miglio, 2013) are also relevant sources of variability, inducing signals of up to several metres per second, depending on the spectral type (Dumusque et al., 2011). For solar-type stars, granulation signals have timescales from a few hours to days, while for p-modes timescales are of the order of a few minutes. An example of the impact of these processes in the RV of the Sun is shown in Figure 1.

Although different approaches are presently used to model the signals produced by these different phenomena, none has proven to correct RV time-series down to the required precision level (for example, Haywood et al., 2022). Furthermore, our incomplete knowledge of stellar physics can also severely impact our ability to detect and characterise exoplanet atmospheres, or even produce systematics that are several times stronger than the ones produced by the planetary atmosphere itself (for example, Casasayas-Barris et al., 2021; Dethier & Tessore, 2024; and see Figure 1). The effects of these phenomena on the measurements of transmission spectroscopy can be particularly problematic, and raise questions such as: if Earth were an exoplanet, would we be able to tell whether it was habitable by observing its atmosphere?

The solar promise

The exoplanet community has recognised that progress in this field requires identifying in detail the different physical processes that drive stellar variations. In this context, the Sun is seen as the ideal target and proxy: it is the only star we can resolve. Dedicated instruments have been built, attached to high-precision spectrographs, to observe the 'Sun-as-a-star' (for example, Zhao et al., 2023). Good examples are the High Accuracy Radial velocity Planet Searcher North (HARPS-N) solar telescope (Dumusque et al., 2021) and its counterpart at the HARPS spectrograph (HELIOS). Overall, these experiments have shed new light on the problem, but also show that our current understanding is still inadequate (for example, Milbourne et al., 2021).

The major drawback of these approaches is the fact that the Sun is observed as a star: only disc integrated spectra are obtained. This precludes a detailed analysis of the individual stellar features responsible for the observed spectral deformations.

The Paranal solar ESPRESSO Telescope

To find new answers we need to obtain disc-resolved, high-precision spectra of the Sun. Similarly to the best instrumentation used in exoplanet research facilities, an adequate instrument has to offer a) spatially resolved spectroscopy with very high wavelength stability, b) very high spectral resolution ($R = \lambda/\Delta\lambda \sim 200\,000$), to adequately resolve photospheric line asymmetries, and c) extended wavelength coverage, for the simultaneous observation of thousands of spectral lines probing different physical conditions. This can be achieved if we link the ESPRESSO spectrograph to a solar telescope: the Paranal solar Espresso Telescope (PoET[1]; see Figure 2).

In a nutshell (see also Leite et al., 2024), PoET will consist of a 600-mm-diameter telescope designed to point to any resolved

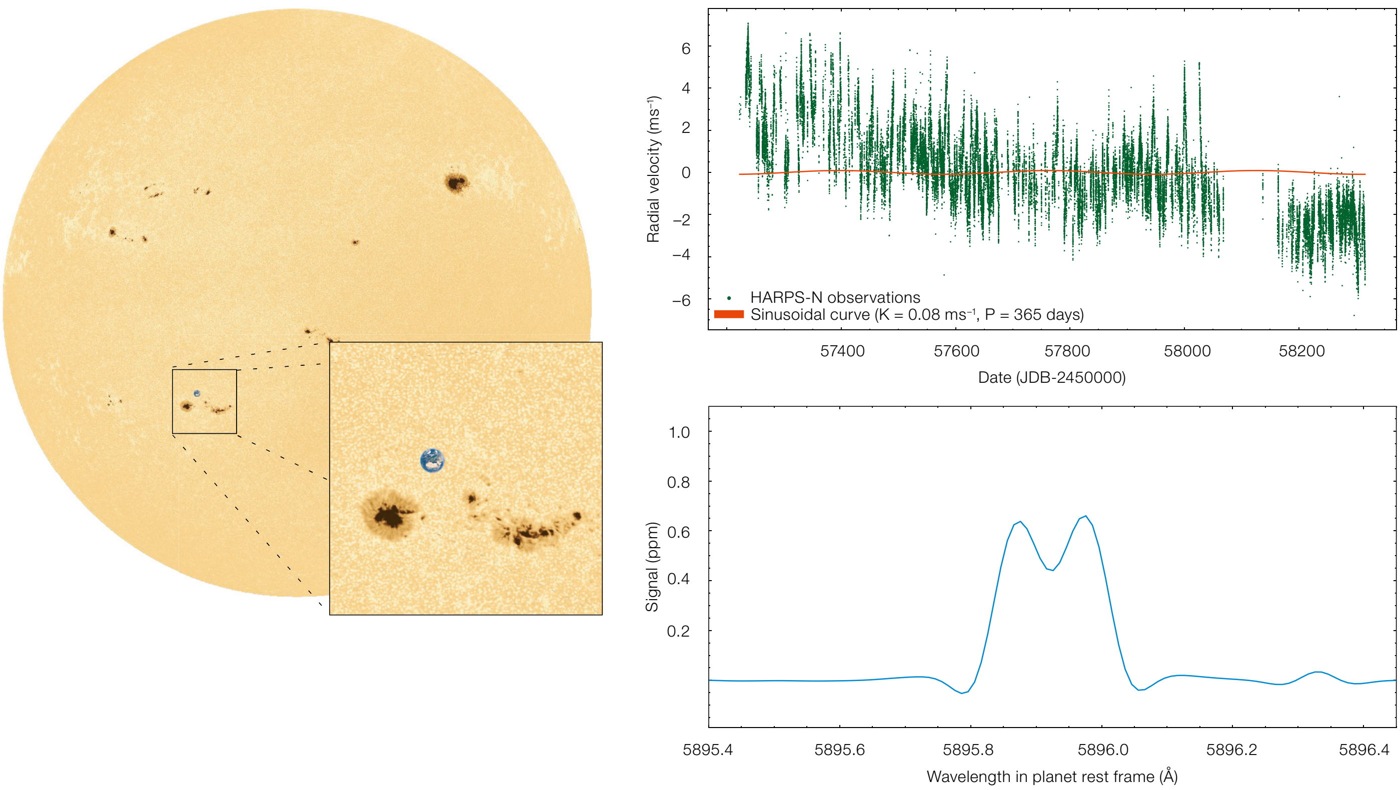

Figure 2. Left: Image of the Sun with Earth superimposed on the same scale. Upper-right: Radial-velocity time-series of the Sun (green points), obtained with the HARPS-N solar telescope (Dumusque et al., 2021), when compared with the expected signature of an Earth-like planet orbiting a Sun-like star (red curve). Lower-right: simulated spurious signature of an absorption spectrum of an atmosphere-less Earth-like planet centered in the sodium line (blue curve), as caused by unaccounted center-to-limb variations. The observed signal has a magnitude level similar to the expected absorption signature of the atmosphere of an Earth-like planet. These plots illustrate the challenges for the detection and characterisation of Earth-like planets orbiting other suns. Image sources: NASA SDO and ESO/M. Kornmesser.

region in the solar disc and inject the light into ESPRESSO using optical fibres. It will observe the Sun on different spatial scales: from 55 arcsec in angular diameter, the typical size of a medium-sized sunspot, down to 1 arcsec, the typical spatial scale of one solar granule. Simultaneous full disc integrated observations ('the-Sun-as-a-star') will also be possible using a piggyback pointing telescope.

Instrument concept

To achieve simultaneous disc-integrated and (arcsecond-level) disc-resolved observations of the Sun, PoET will consist of a three-telescope system, as shown by the simple schematics in Figure 3.

The main telescope (MT) is from Officina Stellare and its objective is the observation of small areas of the solar disc. It has a Gregorian configuration, chosen because of its intermediate focus. This format, a standard for solar observations, enables the introduction of a heat rejector in the intermediate focal plane, rejecting all the light that falls outside of a 4-arcmin-diameter field. This allows heat to be reduced to less than 2% at the level of the frontend focal plane.

Although seeing-limited, one of PoET's scientific objectives is to perform observations with a resolution on the order of an arcsecond, seeing allowing. The selected science apertures are 1, 2, 5, 10, 16, 30 and 55 arcseconds. For reference, 16 arcseconds corresponds to the angular size of Earth as seen from the distance of the Sun. Owing to their small physical dimensions (from 35 μm to 2 mm in diameter) and in accordance with our radiometric model, the selected telescope aperture is required to ensure enough light reaches ESPRESSO in all configurations.

Two simple refractors, the 'science' and the 'imaging' telescopes, known jointly as the pointing telescope (PT), are piggybacked onto the MT. Light from both the MT and the PT will be collected by the respective frontends and, via fibre links, delivered to the ESPRESSO spectrograph via its calibration unit.

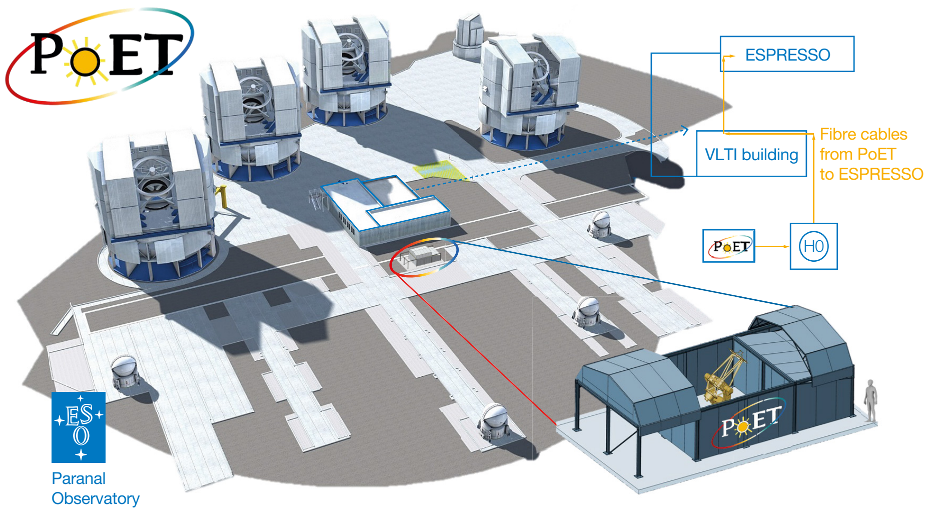

Figure 2. Left: Illustration of the location of PoET in Paranal. Upper-right: Schematic of science fibres path from PoET to ESPRESSO (one floor below). Lower-Right: Dome concept with main telescope.

The PoET frontends

As depicted in Figure 4 (right), in the frontend of the MT, the f/12 beam passes through a 90:10 beam-splitter and is directed to the aperture selector by a folding mirror. The set of different apertures are positioned in the focal plane where light is fed into small fibre patches, either directly (apertures from 1 to 5 arcseconds), through demagnifying lenses (from the remaining apertures) or, alternatively, using an integrating sphere (for the 55-arcsecond mode). The selection is made using a translation stage. The light from the exit of the selected aperture is injected into a double scrambler to guarantee a homogeneous distribution into the science fibre that connects with ESPRESSO.

The apertures are metallic pinholes that reflect part of the incident light back to the beam-splitter and redirect it to a guiding camera (imaging system and sensor), where an image of the observed Sun (with a 3-arcmin-diameter field of view) is registered. This image will indicate the location of the observed region and can be seen with either a 1-nm FWHM Hα filter or a 10-nm red filter (centred on the same region).

The pointing telescope is comparatively much simpler in design (Figure 4, left). A science refractor telescope (achromat lens), with an aperture of 60 mm and focal length of 100 mm, will image the Sun into a 10-mm-diameter integrating sphere that injects the light into the 'Sun's disc-integrated science fibre', connecting to ESPRESSO. A second refractor, with a 50-mm-diameter achromat with a focal length of 350 mm, images the full Sun in the pointing camera sensor. The guiding and pointing cameras will be calibrated to allow the identification of the area to be observed by the MT.

Link to ESPRESSO

The instrument will be installed behind the Very Large Telescope Interferometer (VLTI) building and after the 'no-build zone' (Figure 2). This location was chosen as the preferred site for the instrument based on its relative proximity to ESPRESSO and relatively low wind speeds: to the north, the predominant wind direction, it is 'protected' by the VLTI building, which avoids issues related to vibrations of the telescope structure.

The concept for the telescope dome is a 'sliding roof' design. The roof consists of two sections that open in approximately the west–east direction. The telescope will be hosted in a 5 m × 5 m space. An additional room will be used to house the electronics cabinets, computers, and other auxiliary items.

Science fibres, communication, and power cables will be routed into an unused VLT Auxiliary Telescope hatch (H0), allowing

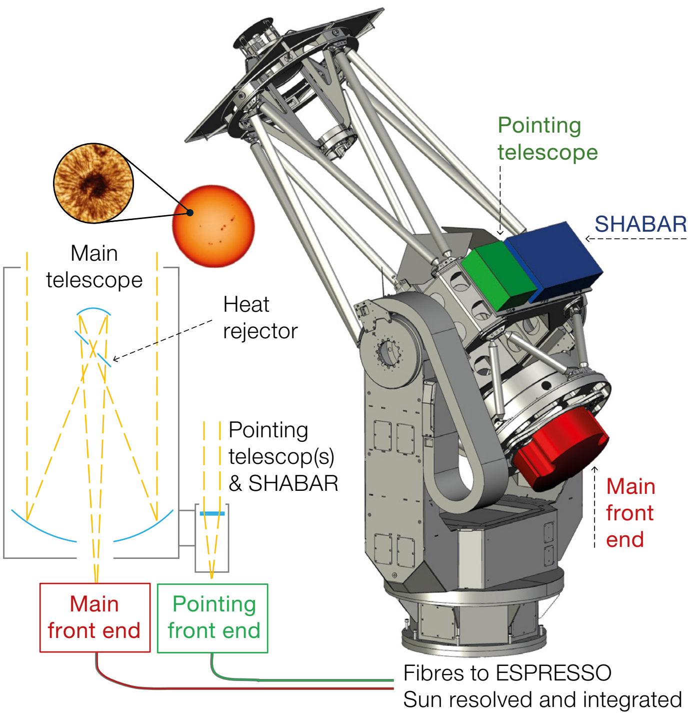

Figure 3. Concept of PoET (left) and scheme of the main telescope (right) with the positioning of the two frontends and the SHABAR seeing measurement device.

easier access for the fibres towards ESPRESSO through the VLTI tunnel, with minimal structural impact. Based on the observatory architectural drawings, we project around 80 m of cable for each science fibre, needed to deliver light collected by PoET towards ESPRESSO's calibration unit, where PoET fibres will be connected. Inside the dome, the science fibres are split via a set of collimators that allow the insertion of a blue filter. Depending on the scientific requirement, this filter can be selected to compensate for the signal loss in the blue region of the spectra, mainly caused by the fibre attenuation.

SHABAR

The MT will receive support from a custom instrument (known as SHABAR) to measure the daylight seeing conditions. Seeing is the effect of random fluctuations in the index of refraction throughout Earth's atmosphere, resulting in random fluctuations in the direction of light from a distant source. Scintillation is the random fluctuation of the light intensity received. A correlation was found between the two. With this concept, and making use of a non-telescopic method, we can measure seeing during the day, using the Sun as the source of light. For this purpose, we built a seeing measurement device, following the same concept as Sliepen et al. (2010), to be used along with PoET. Our SHABAR (Wehbe et al., 2024) is currently commissioned and being tested to be ready for PoET's first light.

Observations, operations and data

As a visitor telescope at ESO's La Silla–Paranal Observatory, PoET is expected to be fully autonomous and not require any local intervention. As such, PoET's software will oversee all operations of the telescope and allow it to run either in a fully autonomous mode or managed remotely from our premises in Portugal. Typically, after the daily calibrations, science operations will run a short script on the ESPRESSO workstation to prepare the instrument to execute PoET–ESPRESSO observations. On its side, the PoET software will create science Observation Blocks (OBs) and ingest them into the ESPRESSO execution sequence through the P2 Application Programming Interface[2]. From then on, and until science operations require ESPRESSO for the preparation of the night operations, PoET–ESPRESSO observations will be executed automatically.

Observations will be made in both high-resolution and ultra-high-resolution modes, at spectral resolutions of ~140 000 and ~200 000, respectively (Pepe et al., 2021). The baseline exposure time used to define the instrumental design is 30 seconds, a compromise between the interest in resolving the solar oscillation signals and the overhead time related to the readout of the ESPRESSO detector.

Several observing modes were defined, leveraging the optical setup of the PoET–ESPRESSO interface and PoET's scientific requirements. The operation modes can be divided into the following categories:

1. Observations of the resolved Sun: in this mode, PoET will acquire high-resolution spectra of a selected (resolved) region of the solar disc using the MT;
2. Resolved solar disc observations with simultaneous 'Sun-as-a-star': in this mode, both the PT and the MT will be injecting light into ESPRESSO;
3. Sun-as-a-star observations with simultaneous wavelength calibration: meant to acquire high-precision radial velocities time-series from disc-integrated exposures ('Sun-as-a-star'), mimicking the usual stellar observations of ESPRESSO.

In all cases, disc-integrated observations will feed ESPRESSO's fibre A, while disc resolved observations will feed fibre B. As a consequence, it will not be possible to obtain simultaneous wavelength calibrations while observing in the disc-resolved mode. This will not impact the science goals of PoET, as ESPRESSO drifts are a few orders of magnitude smaller than the local velocities of the solar disc (for example, due to granulation).

PoET data will be reduced with a new version of the standard ESPRESSO Data Reduction Software (DRS). The DRS will produce the usual ESPRESSO science-grade data products for the different observing modes detailed above. The reduced data will then be complemented with an auxiliary FITS file containing context images from the PoET cameras as well as other relevant information

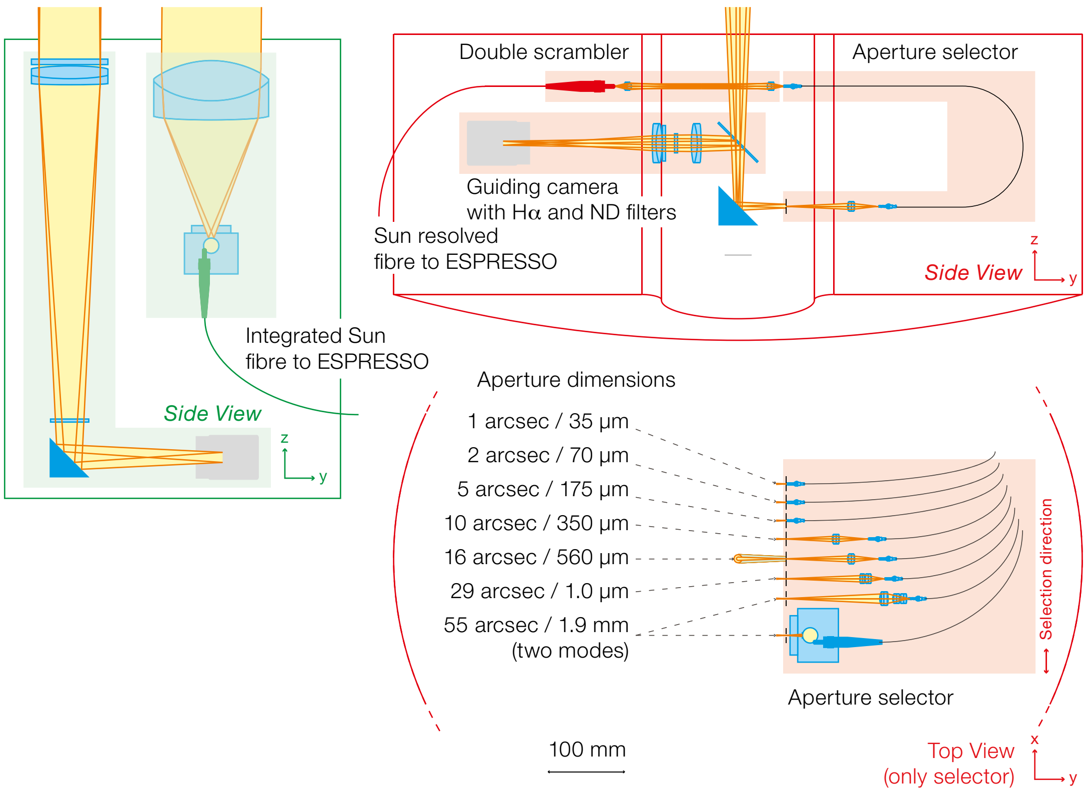

Figure 4. Concept of the two frontends and the fibre injection system and its aperture selector.

(for example, the seeing measured with SHABAR). All data products will be uploaded to the ESO Phase 3 archive.

Timeline and expected science impact

The detailed design of the PoET telescope is now concluded. The procurement of the main components, telescope and mount, as well as the dome, is also in progress. We expect to install the telescope on Paranal in the second semester of 2025 and start operations soon after.

The main scientific motivation behind PoET is to tackle the problem of ‘stellar noise’ in high-resolution spectroscopic observations, both in precise radial velocities and in transmission/emission spectroscopy. This will be fundamental to the success of present and future efforts in exoplanet research, including those linked with ELT instrumentation (for example, ANDES) and ESA missions (for example, PLATO). Moreover, PoET is presently raising interest among several scientific communities, and its data are expected to contribute to other science cases, including solar and stellar physics.

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1 PoET web page: https://poet.iastro.pt
2 ESO Phase 2 API: https://eso.org/sci/observing/phase2/p2intro/Phase2API.html
3 PoET workshops: https://poet.iastro.pt/events/

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Flux Calibration for VLT and ELT Spectrographs

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ESO offers a range of optical and infrared spectrographs on its telescopes, and more will be available once ESO's Extremely Large Telescope (ELT) starts operating. Some, but not all, science cases require the flux of spectra to be calibrated in relative or absolute units. The achievable accuracy of such a flux calibration differs with circumstances and instrument. In this article, we provide an overview of the methods and routinely obtained accuracy for current Very Large Telescope and future ELT spectrographs.

Introduction

Spectroscopic flux calibration means the conversion of a spectrum from the measured signal in e^{-} s^{-1} to physical flux units (erg cm^{-2} s^{-1} $Å^{-1}$ or W m^{-2} nm^{-1}). The wavelength dependent conversion is usually derived from the observations of spectrophotometric standard stars, whose absolute flux distributions are well known. A 'response curve' is determined by taking the ratio of the absolute flux distribution and the observed spectrum. Reduced science spectra are then multiplied by this response curve to flux-calibrate them.

There are two types of flux calibration, absolute and relative. Absolute flux calibration, by which the observed flux of a spectrum is converted to absolute flux units, is comparable to the photometric calibration of images. Absolutely flux-calibrated spectra represent the correct flux distribution of the object, both in value and shape, and can thus be compared directly to independently observed photometry or model spectra. Absolute flux calibration requires that the total flux that enters the telescope, for both the standard star and the science target, can be determined, and that the wavelength-dependent extinction for both a flux calibrator and the science observations can be determined. The former requirement is difficult to satisfy since flux lost by the finite slit width or fibre diameter needs to be measured or modelled. The latter requirement demands an accurate characterisation of the atmospheric conditions during a particular observing night.

For many science cases, such as radial-velocity or equivalent-width measurements, an absolute flux calibration is not necessary, and a relative flux calibration is sufficient to reach the science goals. Relative flux calibration corrects only the instrumental signatures in the spectra, such as for instance the spectral energy distribution (SED) of the flat field in the case of echelle data. Such a calibration results in spectra that are free from small-scale artefacts caused by the instrument such as wiggles and bumps, but the overall shape of the continuum may not accurately represent the physical flux distribution of the observed object. Reasons for discrepancies between the observed and the true shape include unaccounted slit losses, differences between the assumed and the actual extinction, and variations in extinction or instrument response between the observations of the standard star and the science target.

In this paper, we provide an overview of the methods and accuracy of spectral flux calibration of currently active Very Large Telescope (VLT) spectroscopic instruments.

VLT spectroscopic standard stars

Spectroscopic flux calibration relies on the availability of sufficiently bright spectroscopic standards with known absolute flux. These standards are then regularly observed to calibrate the combined throughput of the atmosphere, telescope and instrument optics. From these observations, a response curve can be derived. The response curve can then be used to convert, for a given airmass and instrument setup, the photon counts of a raw spectrum to physical units. The response needs to be tracked because of long-term changes in the instrument and telescope (for example, mirror reflectivity), as well as changing atmospheric conditions (for example, CO_2 or ozone abundance). Ideally the spectrum of a spectrophotometric standard star contains neither emission nor absorption lines, because such features can cause residuals in the ratio between reference spectrum and observed data, as a result of different resolution, imperfect wavelength calibration or radial velocity differences.

Traditionally, reference data with a variety of resolutions and accuracy, derived from ground-based or space-based observations for various spectral types, have been employed for flux calibration of VLT spectrographs. The most widely used catalogues for optical spectrographs are those from Hamuy et al. (1994) and the CALSPEC database of the Hubble Space Telescope (Bohlin, Gordon & Tremblay, 2014[1]; most of which are too bright and/or too northern for the VLT spectrographs). The data from Oke (1990) have systematic problems (as described in the original publication) and are therefore no longer used for any VLT instruments.

For observations in the infrared wavelength range spectrophotometric standards that are used for optical wavelength ranges are not necessarily suitable, because their spectra are usually known only up to about 1000 nm, and redder parts could contain spectral features or additional flux that affect the response determination. The VLT Imager and Spectrometer for mid-InfraRed (VISIR) uses as reference data spectral templates for late-type stars from Cohen et al. (1999) and the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES+) uses model spectra of optical spectrophotometric standard stars of spectral types B4-A9.

For medium-resolution spectrographs covering wavelengths from the ultraviolet to the near-infrared like X-shooter, accurate photometric reference data are difficult to obtain. In such cases, stellar model spectra of hot white dwarfs can be used for flux calibration. The advantages of using model spectra (which are also available for some of the CALSPEC stars) are high spectral resolution and the absence of noise and atmospheric absorption features like telluric lines. Model spectra can be determined to a high level of accuracy for hot white dwarfs, which have relatively simple atmospheres, especially when compared to cool main sequence stars. From a practical point of view their spectra offer another advantage in that they have a small number of smooth and wide

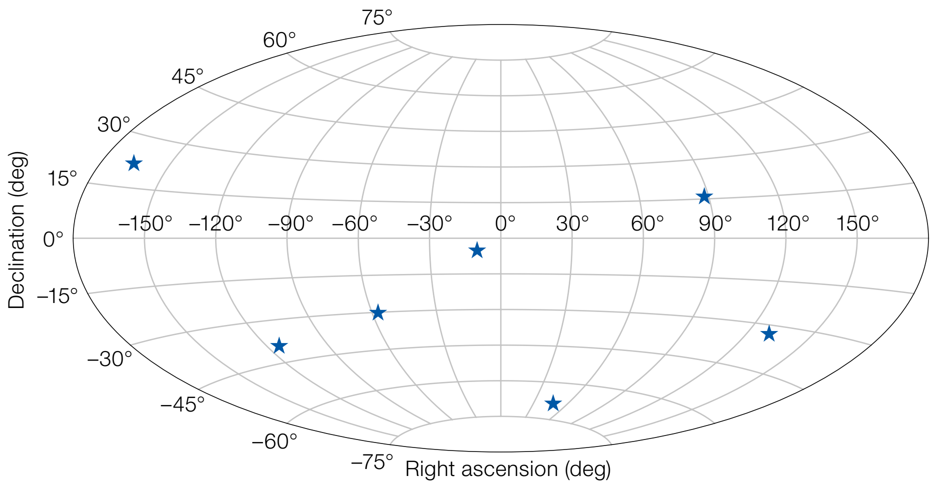

Figure 1. Distribution of the X-shooter spectrophotometric standard stars on the sky. The two northern stars are the HST CALSPEC standard stars GD71 and GD153.

absorption lines. This limits the impact of small deficiencies in the wavelength calibration or differences in resolution compared to the case of cool main sequence star spectra with many more and much narrower lines.

The finely sampled noise-free model spectra can be interpolated to the observed wavelength grid, so that the ratio of the reference and observed spectra can be determined at the full instrumental resolution instead of having to integrate the flux to the large bin size of low-resolution empirical reference data. This enables the fitting of small-scale instrumental variations that were previously lost. X-shooter was the first VLT instrument for which this approach was implemented consistently. The sample of X-shooter flux standard stars consist of six hot, white, hydrogen-atmosphere white dwarfs (two of which are also part of CALSPEC) and one hot, helium-rich pre-white dwarf. Figure 1 shows their distribution on the sky. Because the model spectra used as reference data do not contain telluric absorption, which becomes substantial in the near-infrared, a simple telluric correction was implemented. In addition, fit points were defined to avoid regions of very strong telluric absorption as well as the cores of the stellar lines, where differences in resolution and/or radial velocity can create strong but narrow residuals. The median values of the raw response over pre-defined windows at the fit points are then used to fit the response curve. More details can be found in Moehler et al. (2014). The overall slope of flux calibration using these model spectra is accurate to about 5% (Sana et al., 2024)

Calibration of VLT spectrographs

ESO operates a range of spectrographs that serve different science use cases and employ a range of different techniques to produce data of different natures. Accordingly, the flux calibration for each of them follows a specific plan. This calibration plan for each instrument is available at the instrument web pages[2].

Long-slit spectrographs

The three optical/NIR slit spectrographs currently operated at the VLT (the FOcal Reducer and low dispersion Spectrograph 2 [FORS2], the Ultraviolet and Visual Echelle Spectrograph [UVES], and X-shooter) perform only relative flux calibration, because the science targets are generally observed with narrow slits and the slit losses are hard to quantify automatically. Readers interested in this issue are referred to Chen et al. (2014) and Manara et al. (2021).

The experience with the X-shooter flux calibration resulted in the switch of the UVES reference data from the previous inhomogeneous collection to the X-shooter stars in 2020. Figure 2 compares the spectrum of the star κ Lep calibrated using the old and new reference data and pipelines[3]. One can clearly see that finely sampled reference data are required to catch the small-scale variations in the instrument response.

Observed spectra are affected by telluric absorption, whereas the physical stellar model spectra used as a comparison are not. In order to maximise the wavelength range usable to compute the response curve, the observed spectra are corrected for telluric absorption which depends on the atmospheric condition at the time of observation. In the X-shooter pipeline this correction is performed by selecting the best-fitting telluric model spectra from a library of model spectra (Kausch et al., 2015). For UVES spectra, wavelength regions with strong telluric absorption are excluded from the fit in the standard settings of 760 nm and 860 nm.

FORS2, with its lower resolution, has so far relied primarily on the standard stars of Hamuy et al. (1994). The spectra were masked to avoid telluric and stellar lines, which in some cases resulted in a large fraction of the spectrum being masked. The FORS pipeline is currently being updated to use the same standard stars and methods as UVES and X-shooter. In the case of FORS, the standard-star model spectra are convolved to lower spectral resolution to avoid large residuals. The telluric correction is carried out by directly fitting a physical model to the observed spectra (Smette et al., 2015; Kausch et al., 2015). The latest release of the FORS pipeline contains these improvements.

Fibre spectrographs (ESPRESSO)

The Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) is a high-resolution spectrograph that uses fibres instead of physical slits. Several fibres are used to form a ‘pseudo slit’. The total flux collected by a fibre depends on the exact two-dimensional positioning of the fibres relative to the source. It is therefore even more challenging to quantify the ‘slit’ losses for a particular observation.

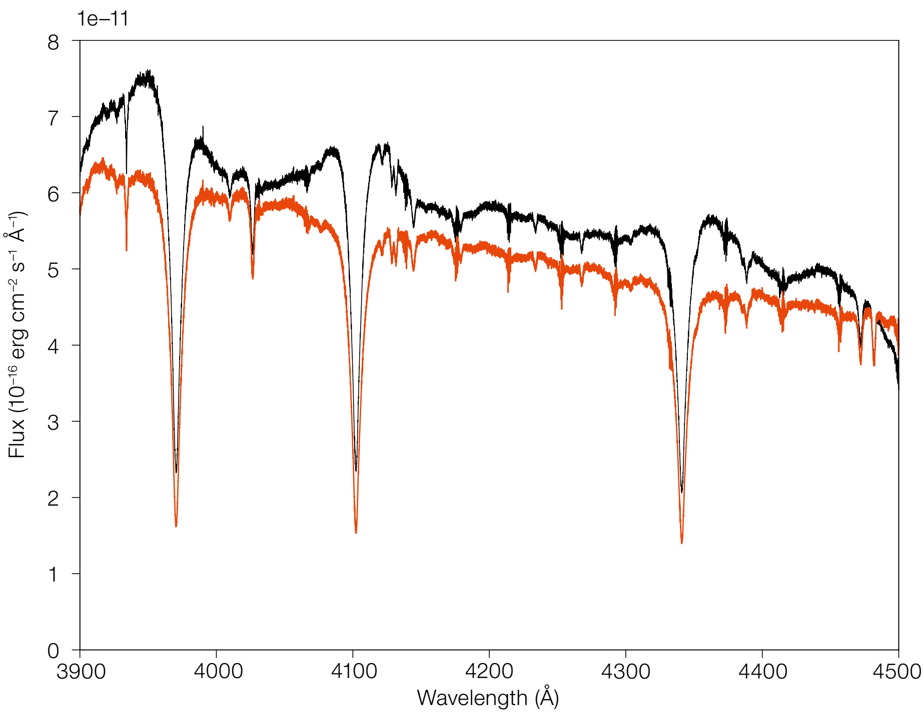

Figure 2. Comparison of the flux-calibrated spectrum for the bright star κ Lep (observed 2019-01-17T01:01:23.629), processed with the response curve derived from the associated flux standard star EG21. The black spectrum shows the result of the flux calibration using the old UVES response determination, the red one the result using the new UVES response determination (offset for easier comparison).

ESPRESSO uses very low-resolution spectra of bright stars derived from ground-based observations (Hamuy et al., 1994), i.e., including telluric absorption, as reference data. The pipeline corrects the observed flux for slit losses taking into account the seeing (described by a Moffat function) compared to the diameter of the fibre. Slit losses become significant if the seeing disc is larger than the fibre. The effects of positioning uncertainty are not considered. The pipeline computes the absolute efficiency at reference wavelengths by comparing it to the reference spectrum. The result is then interpolated to the ESPRESSO wavelength scale using cubic splines. The precision of the flux calibration is expected to be low because of the highly variable fibre losses.

Integral field spectrographs (MUSE, KMOS, ERIS-SPIFFIER)

Integral field spectrographs (IFUs) produce full position–wavelength cubes of a field using an image slicer that cuts the field of view into slices that are then fed to spectrographs. They do not suffer from slit losses during the observation since the flux is collected mostly independent of the positioning of the sources relative to the detector. Slit losses can occur during the extraction of spectra for individual targets, but these can in principle be quantified to very high accuracy. The goal of the flux calibration of IFUs is to convert the total flux contained within each wavelength plane of the data cube to physical units.

The Multi Unit Spectroscopic Explorer (MUSE) provides absolute flux calibration and uses a mixed set of reference spectra, some of them high-resolution model spectra and some data observed from space with lower resolution, all without telluric absorption. The MUSE resolution is sufficiently low to cause problems if high-resolution model spectra are used as reference data without convolving them first to a lower resolution, as for FORS2. The pipeline determines a first response curve by comparing the observed spectrum to the reference one. Next it interpolates across regions of telluric absorption and determines a telluric correction spectrum from the normalised spectrum, assuming that the standard star spectrum is smooth across the telluric regions. The final response curve is then linearly extrapolated to the largest possible wavelength range and smoothed.

The *K*-band Multi Object Spectrograph (KMOS) also provides absolute flux calibration but uses as reference data hard-coded model spectra per spectral type and magnitude, which consist of a Planck blackbody curve with added absorption lines, whose depth is adjusted to the observed data. The final response curve is thus a combination of instrumental response and telluric absorption

The Enhanced Resolution Imager and Spectrograph (ERIS-SPIFFIER) uses the same standard stars as X-shooter and a similar procedure to determine the response curves.

Spectrographs without flux calibration

The VLT spectrographs VISIR (slit) and CRIRES+ (fibre) monitor the instrument throughput/efficiency using standard stars, but do not flux-calibrate the science data. For details see Table 1.

For a multi-fibre instrument like GIRAFFE the cost of observing time to obtain flux calibration was considered too high. The throughput of the instrument is monitored only in the IFU (ARGUS) mode.

The ERIS Near Infrared Camera System (ERIS-NIX) instead does not monitor the efficiency of its long-slit mode because there are no suitable flux standard stars for the *L* and *M* bands.

The Spectro-Polarimetric High-contrast Exoplanet REsearch instrument Integral Field Spectrograph (SPHERE-IFS) observes some of the CRIRES flux standard stars, but the data are not processed.

ELT spectrographs

All Extremely Large Telescope (ELT) instruments will use adaptive optics, which can cause variable flux losses

Instrument	Mode	Wavelength coverage (microns)	Resolution	Flux calibration	Telluric correction of flux std	Source for reference data	Type of reference data	Accuracy of flux calibration
CRIRES+	Slit	0.95–5.3	43000 / 86000	No, science goals do not require it – this instrument is designed to measure radial velocities and weak lines; efficiency monitoring only	No	Model spectra from T. Rauch & P. Coelho (priv. comm.)	Model	N/A
ERIS NIX	Slit	3.05–4.05	900	No, no *L* or *M* band spectro-photometric standards are available	N/A	N/A	N/A	N/A
ERIS SPIFFIER	IFU	1.09–2.47	5000 / 10000	Yes	Yes	Moehler et al. (2014)	Model	Unknown
ESPRESSO	Fiber	0.38–0.79	70000–190000	Yes	No	Hamuy et al. (1994) (HR stars)	Ground	Unknown
FORS2	Slit	0.33–1.1	260–5200	Yes	No	ground Hamuy et al. (1994); space/model HST CALSPEC	Ground / model / space	Unknown
GIRAFFE	Fiber	0.37–0.95	11000–39000	No, because science cases do not need it; observations of flux standards are not part of the calibration plan	N/A	N/A	N/A	N/A
GIRAFFE	IFU	0.37–0.95	11000–39000	No, because science cases do not need it; efficiency monitoring only	No	N/A	N/A	N/A
KMOS	IFU	0.8–2.5	2000–4200	Yes	No	Extended Hipparcos Compilation (XHIP) (Anderson & Francis, 2012)	Model (blackbody + absorption lines, based on spectral type)	10% on continum ~15% wiggles in case of good seeing observations
MUSE	IFU	0.47–0.93	3000	Yes	Yes	Moehler et al. (2014); CALSPEC (HST)	Model / space	Continuum 5–10%, with long-scale wiggles < 5%
SPHERE	IFU	0.95–1.65	30 / 50	No, because science casse do need it;observations of flux standards are not part of the calibration plan	N/A	N/A	N/A	N/A
UVES	Slit	0.3–1.1	40000–110000	Yes	No	Moehler et al. (2014)	Model	Unknown
VISIR	Slit	7.7–24.0	350 / 25000	No, because flux uncertainty is dominated by the extremely high background, the sources are a percent or less than the sky contribution and the Poisson errors form the background is huge;efficiency monitoring only	No	Cohen et al. (1999)	Space	N/A
X-shooter	Slit	0.3–2.5	3200–18400	Yes	Yes	Moehler et al. (2014)	Model	Small-scale wriggles about 2%; slope about 5–10% (Sana et al., 2024)

Table 1. An overview of the type of flux calibration implemented at the VLT spectrographs.

and therefore present special calibration challenges that are not addressed here.

The High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI) provides low- to medium-resolution IFU spectroscopy at 0.45–2.8 microns over a range of resolving powers and will use the X-shooter flux standard stars.

The Mid-infrared ELT Imager and Spectrograph (METIS) provides high-resolution IFU spectroscopy at 3–5 microns and low-resolution slit spectroscopy at 3–13 microns. It will use the same flux standard stars as VISIR.

The Multi-AO Imaging Camera for Deep Observations (MICADO) offers medium-resolution IFU and slit spectroscopy at 0.8–2.5 microns. Suitable flux standard stars have been defined from X-shooter observations of nearby hot white dwarfs.

Summary

Spectrophotometry can be carried out with the majority of VLT spectrographs, although with varying accuracy. A summary of the current state is given in Table 1. The calibration plan for flux calibration is the result of a careful instrument-specific cost-benefit analysis for each instrument, that might evolve over the course of time. In some cases, it might be necessary for science programmes to collect additional calibration data to improve on the flux calibration that can be achieved with the standard calibration plan. Any additional time needed for such extra nighttime calibrations must already be requested in Phase 1.

Acknowledgements

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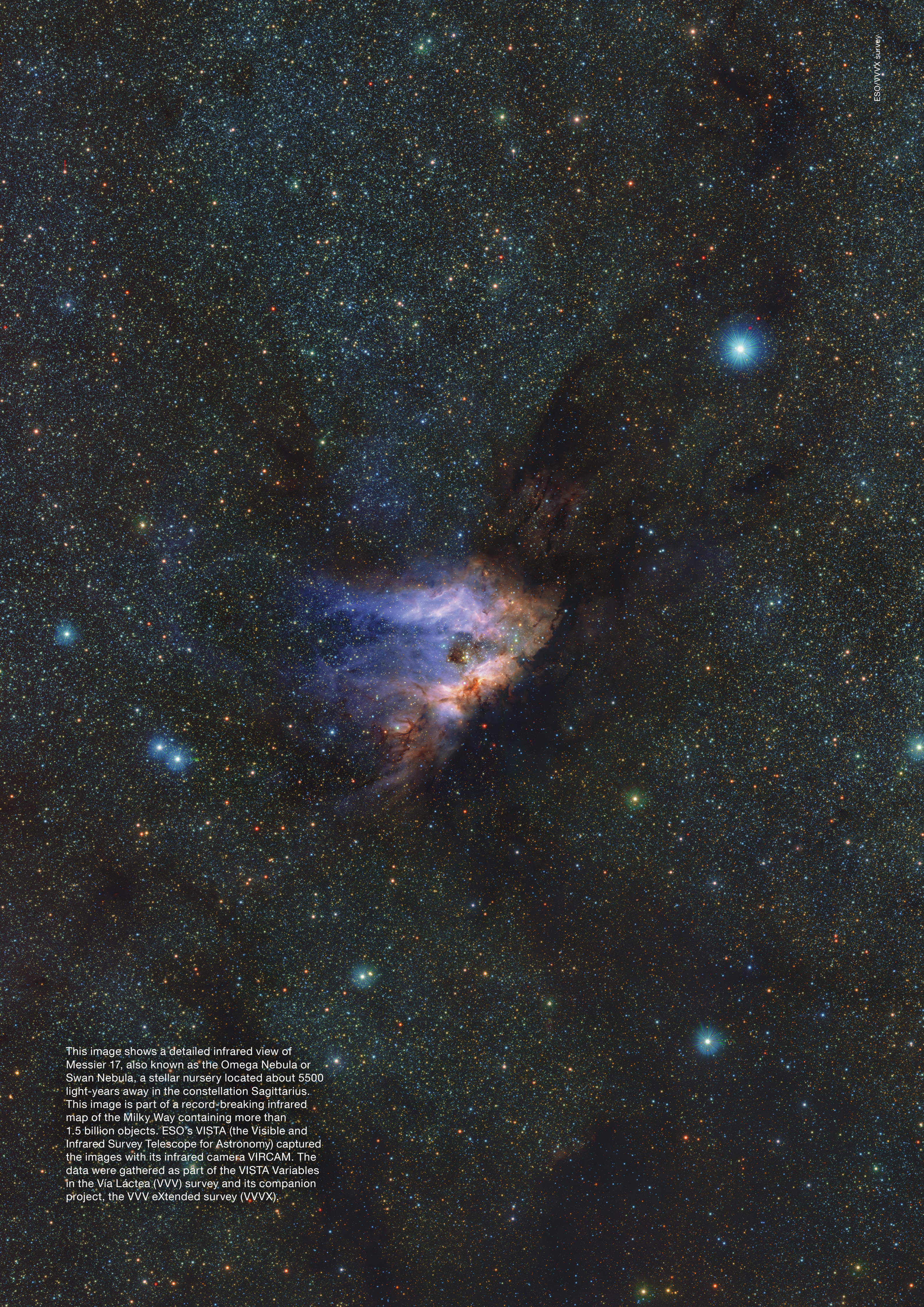
Links

[1] CALSPEC database: https://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/astronomical-catalogs/calspec
[2] Paranal instrument details: http://www.eso.org/sci/facilities/paranal/instruments.html
[3] ESO data reduction pipelines: https://www.eso.org/sci/software/pipe_aem_main.html

Y. Beletsky (LCO)/ESO

Looking almost like a watercolour painting, this stunning photograph of comet C/2024 G3 (ATLAS) was taken by Yuri Beletsky on 19 January from ESO's Paranal Observatory in Chile. The comet poses next to one of the Auxiliary Telescopes of ESO's Very Large Telescope Interferometer.



ESO/VVVX survey

This image shows a detailed infrared view of Messier 17, also known as the Omega Nebula or Swan Nebula, a stellar nursery located about 5500 light-years away in the constellation Sagittarius. This image is part of a record-breaking infrared map of the Milky Way containing more than 1.5 billion objects. ESO's VISTA (the Visible and Infrared Survey Telescope for Astronomy) captured the images with its infrared camera VIRCAM. The data were gathered as part of the VISTA Variables in the Vía Láctea (VVV) survey and its companion project, the VVV eXtended survey (VVVX).

F. Millour/ESO

Apart from actually going into space, you probably won't feel much closer to the stars than at the top of the staircase at ESO's Paranal Observatory shown in this picture. At 2635 metres (plus some twenty steps) above sea level in the Atacama Desert of Chile, you see a wealth of stars that remain hidden in other places, because Paranal boasts the darkest skies of all major observatories on Earth.

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Distributed Peer Review at ESO: Demonstrating Success and Evolving Through Period 115

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ESO's Distributed Peer Review (DPR) has transformed proposal evaluations by fostering efficiency and community involvement, making it an essential tool for handling the large volume of proposals traditional panels cannot review alone. A key strength of DPR is its inclusion of the entire community, engaging researchers at all career levels and identifying expert reviewers. This article summarises updated findings up to Period 115, focusing on expertise assignment, DPR comment usefulness and user satisfaction. DPR's success supports its planned expansion into fast-track channels and yearly cycles. ESO is also exploring further innovations to optimise this process.

Introduction

The Distributed Peer Review (DPR) paradigm has emerged as a promising alternative to traditional expert panel reviews, driven by the rapidly growing number of proposals submitted to large astronomical facilities. By actively involving Principal Investigators (PIs) and Co-Investigators (Co-Is) in reviewing one another's proposals, DPR seeks to distribute the workload more evenly while maintaining the quality of evaluations. After initial deployments at Gemini Observatory, ESO conducted an early pilot project (Patat et al., 2019), and the Atacama Large Millimeter/submillimeter Array (ALMA) introduced DPR for its Cycle 8 (although based on rankings, not grades as for ESO; Carpenter et al., 2022). The first comprehensive assessment of ESO's DPR outcomes was presented by Jerabkova et al. (2023), laying a solid foundation for broader adoption. In this article, we update and expand upon these insights through Period 115.

Background and objectives

The DPR process aligns with ESO's commitment to fairness and efficiency in proposal evaluations, introduced as a necessary tool to manage the growing number of proposals that made it challenging for traditional panels to maintain high-quality reviews. At present, ESO assigns proposals requesting less than 16 hours of observing time — around 50% of all proposals but only 20% of the allocated time — to DPR, while panels still oversee most of the time allocation. Potentially sensitive cases, such as joint programs with ALMA, XMM-Newton and other exceptions, are reviewed by panels irrespective of the time request, as outlined in ESO's DPR guidelines[1]. The choice to maintain both DPR and traditional panels offers ESO valuable flexibility, allowing it to address specific proposal types that may require panel oversight in the future. This hybrid system, with DPR alleviating the workload on panels, ensures that panels can maintain a high standard of review quality. The DPR system leverages ESO's User Portal, where each user is required to provide two to five keywords representing their scientific expertise. Similarly, proposals include selected keywords from the same pool, which are used to calculate expertise-match scores between reviewers and proposals. These scores are central to the proposal distribution process. Each submitting team, represented by a PI, must nominate one reviewer who is responsible for evaluating DPR-assigned proposals from their peers.

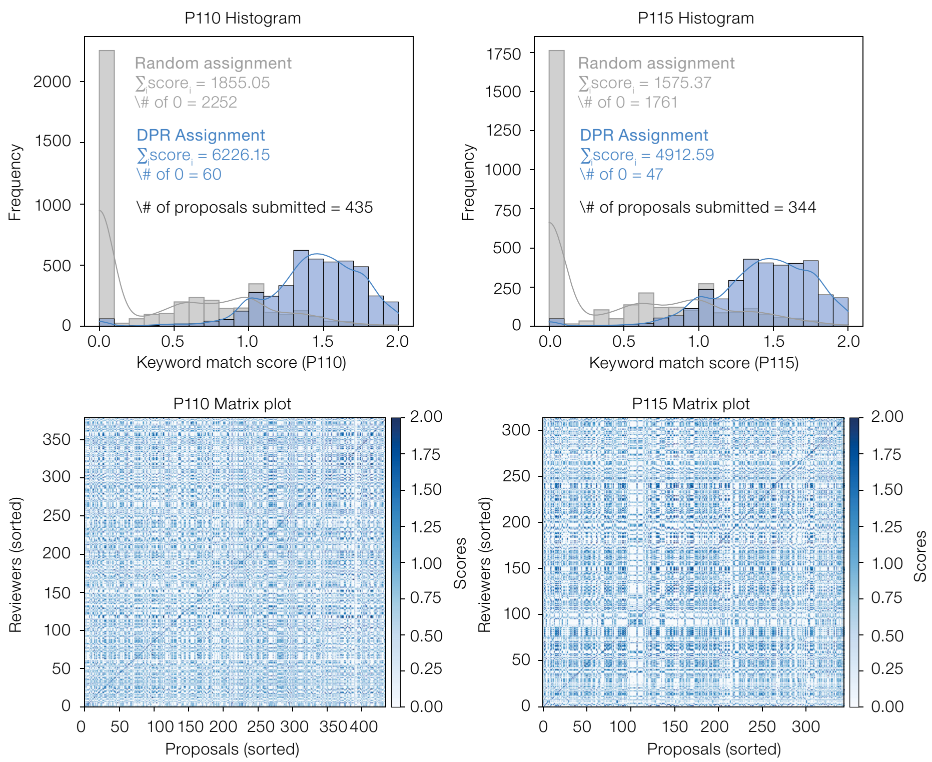

Figure 1. Expert reviewer assignments in the DPR for Period 110 (left) and Period 115 (right). The bottom panels present the *assignment matrix*, in which DPR proposals are on the horizontal axis and DPR reviewers on the vertical axis. Although the matrix is not square, it is sorted so that the main diagonal corresponds to each proposal's delegated reviewer — often the PI or a co-I. The colourmap shows keyword-based expertise scores: a high score along the diagonal verifies that PIs or co-Is indeed have strong expertise for their own proposals, serving as a self-consistency check.

In the top panels, the grey lines indicate how a purely random assignment would appear. Because most keyword-matched scores are zero, the random assignment fails to align expertise with proposals. By contrast, the final assignment (shown in blue) largely avoids zero-score pairings, confirming the necessity of a more sophisticated reviewer assignment process.

Figure 2. Comparison between the reviewer-proposal match scores — calculated from specified keywords — and reviewers' self-assessed expertise. This Figure demonstrates how closely the keyword-based matching aligns with the reviewers' own perception of their expertise, serving as a validation for the automated assignment approach.

Key findings and updates

Algorithm performance

The assignment algorithm remains a critical component of DPR's success. As illustrated in Figure 1, the final matching of proposals to reviewers outperforms a purely random approach, resulting in an optimal distribution of expertise across the submitted proposals. This robust method ensures the integrity of the review process, even as the number of proposals and reviewers continues to grow. In our previous work (Jerabkova et al., 2023), we focused on Period 110 and partially on Period 111, establishing the first statistical analysis of the DPR's performance. Building on those findings, the current results reinforce how crucial it is to match each proposal with a suitably qualified reviewer.

Advantages and challenges of keyword-based assignments

Keywords continue to play a dual role in facilitating expertise matching. On the positive side, they are intuitive to set and interpret, enabling the community to self-regulate how expertise is represented. However, some challenges persist:

1. Static Nature of Keywords: because keywords do not automatically evolve alongside rapidly advancing scientific fields, mismatches can arise over time.
2. User Inconsistencies: Some users fail to update their keywords regularly, or they assign them improperly, both of which can adversely affect the accuracy of reviewer–proposal matches.

Figure 2 demonstrates the link between keyword-based match scores and reviewers' self-identified expertise. While these results validate the general reliability of using keyword vectors to define reviewer expertise, they also underscore potential pitfalls arising from outdated or misapplied keywords. Ongoing efforts by Amado et al. (in preparation) aim to refine the keyword framework, making it more flexible and adaptive to scientific evolution. In parallel, ESO is communicating closely with ALMA, which has begun adopting a machine learning approach for reviewer assignments (Carpenter, Corvillón & Shah, 2024).

By addressing the limitations of keyword-based assignments and leveraging emerging technologies, DPR can continue to evolve as a sustainable and fair peer-review method that adapts to an ever-increasing volume of astronomical proposals.

User satisfaction

Jerabkova et al. (2023) first examined user satisfaction data from Period 110, finding that feedback under DPR was generally better received than traditional panel comments — especially for rejected proposals, where constructive input is critical. Subsequent user surveys are systematically run each Period. They are built into the DPR evaluation system and receive responses from typically 50% of the PIs. The outcomes indicate that since the implementation of DPR PIs with accepted proposals consistently rate DPR feedback as valuable, whereas rejected proposals attract more mixed responses. Despite these variations, a large fraction of DPR users now report that comments

Table 1. Summary for each period for both DPR and panels.

Period	Proposals	Feedback	Accepted	Rejected	%
DPR P110	435	1358	349	1009	31.22%
Panel P110	429	124	50	74	28.90%
DPR P111	419	2708	1138	1570	64.63%
Panel P111	401	247	121	126	61.60%
DPR P112	451	1911	732	1179	42.37%
Panel P112	442	222	113	109	50.23%
DPR P113	402	2555	1239	1316	63.56%
Panel P113	378	206	112	94	54.50%
DPR P114	403	2413	1003	1410	59.91%
Panel P114	448	245	134	111	54.69%
DPR P115	344	1481	698	783	43.05%
Panel P115	416	123	73	50	29.57%

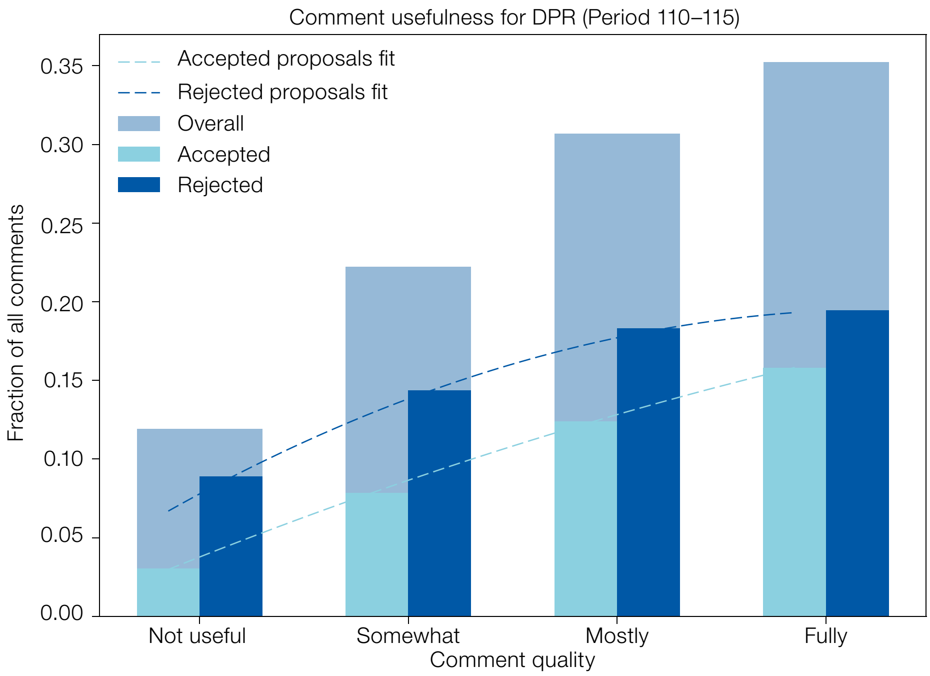

Figure 3. Histogram of user ratings for DPR feedback spanning Periods 110–115. The four categories — *not useful, somewhat useful, mostly useful, fully useful* — reflect PIs' perceptions of review comments they received. The left panel (or first subplot) shows ratings for accepted proposals, and the right panel (or second subplot) shows ratings for rejected proposals. A notable uptick in *fully useful* feedback is seen over time for both categories, suggesting that DPR has steadily improved in delivering constructive and actionable comments.

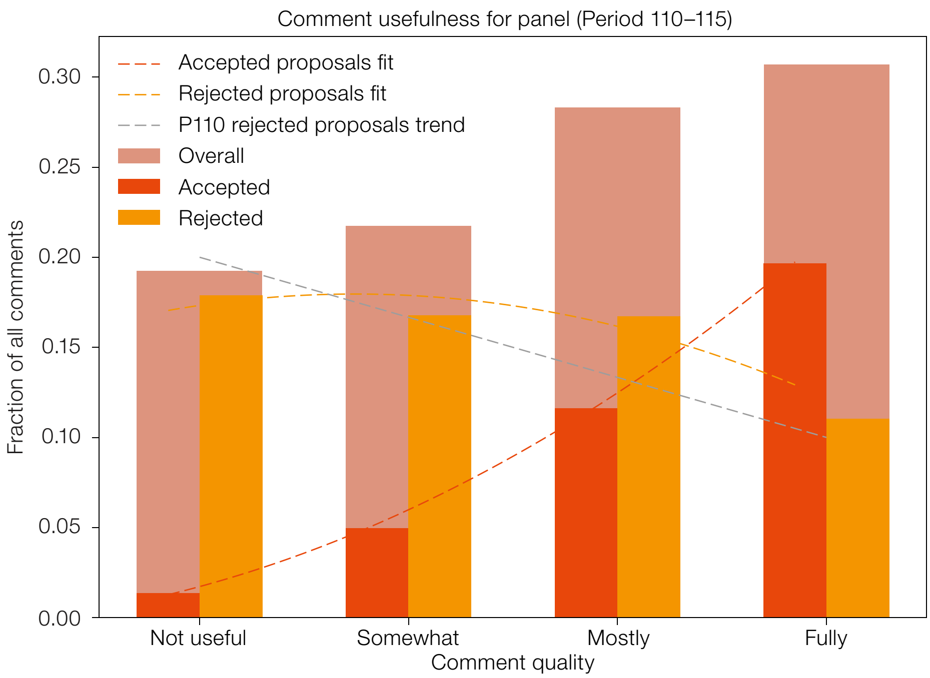

Figure 4. The same as Figure 3, but illustrating user ratings of panel reviews over Periods 110–115. While user satisfaction with panel comments remains lower overall compared to DPR, an upward trend in *mostly* and *fully useful* ratings is observed — particularly for accepted proposals. This improvement may stem from reduced reviewer workloads, thanks to the adoption of DPR, which allows panels to dedicate more time to each proposal. However, panel comments for rejected proposals still show less favourable ratings, indicating the need for continued attention to feedback quality in these cases.

are mostly or fully useful, underscoring the value of this more distributed approach to peer review.

In parallel, panel-based evaluations have shown some improvement over the same periods, likely thanks to the 50% reduction in workload made possible by DPR. Historically, users have viewed panel feedback — especially for rejected proposals — as less beneficial, a sentiment strongly reflected in the Period 110 survey results. However, current data (spanning Periods 110 to 115), as shown in Figures 3 and 4, reveal a modest but encouraging upswing in the proportion of panel comments deemed mostly or fully useful, at least for accepted proposals. While this positive trend has not yet matched DPR levels, it offers promise that, with continued effort and streamlined workloads, panel comments can further improve — particularly where it matters most, i.e. for proposals that ultimately receive a rejection. Table 1 shows a number summary for each period for both DPR and panels, showing that the analysis is based on robust numbers.

Career stage and reviewer bias

Analyses of DPR grading trends reveal no statistically significant bias in the scores assigned by reviewers at different career stages. Although there is a slight tendency for senior scientists to award poorer grades, students continue to be a pivotal part of the process, often providing some of the most constructive and well-received comments. These observations are consistent with earlier results (Jerabkova et al., 2023), reinforcing the conclusion that career-stage differences are not a major driver of bias in the DPR framework.

An additional point worth highlighting is the inclusivity of the DPR model, which allows students and junior researchers to serve as reviewers — an option not typically available under traditional panels. Interestingly, the feedback they supply is frequently rated as most useful by proposal authors (see Figure 5), validating the merit of incorporating perspectives from earlier-career scientists. When students or junior researchers feel uncertain about their evaluations, they may request permission to consult their supervisors, who must abide by the same confidentiality

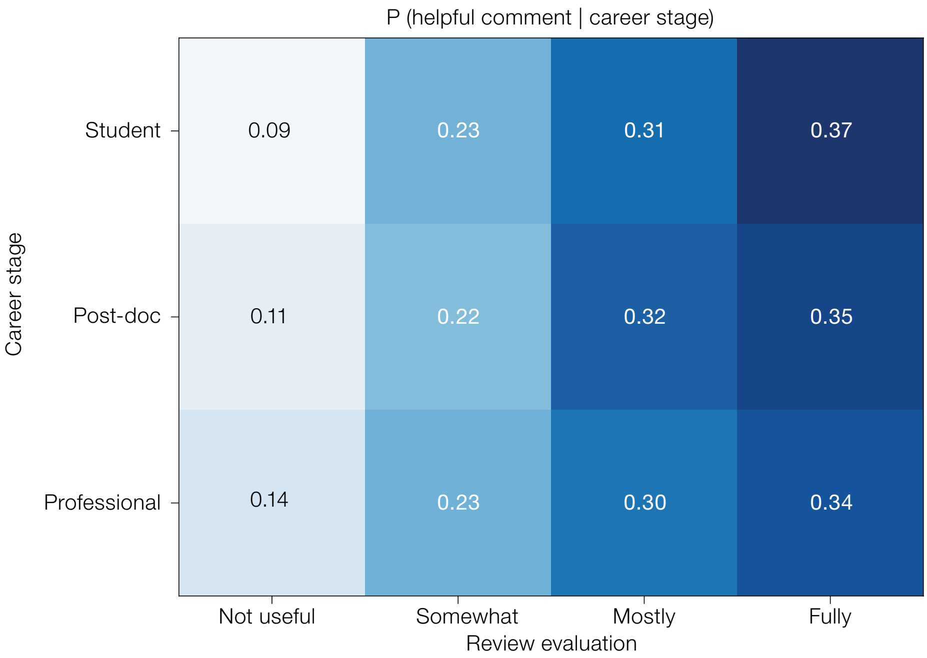

Figure 5. Color-coded conditional probability map showing how perceived comment usefulness varies with reviewer career stage in the DPR. Each bin displays the probability that a reviewer at a given career stage receives a specific usefulness rating from the PIs, with values normalized across the usefulness axis (i.e. each row sums to one). The data confirm that comments from students are consistently rated as highly useful, while senior researchers — though often more stringent in grading — also provide valuable, high-quality feedback. These results align with findings from Period 110, reinforcing the important contribution of early-career scientists to the peer-review process.

agreements. This process has been invoked in several instances each semester, helping to ensure that reviewers at all career stages can participate confidently and responsibly.

Reviewer demographics and diversity

One notable aspect of DPR is that the reviewer pool reflects the broader community, with a slight overrepresentation of postdoctoral researchers. Unlike traditional panels, ESO does not control the composition of DPR reviewers in terms of gender, seniority or nationality. In contrast, panel composition is carefully curated to ensure diversity across these dimensions (Primas et al., 2024; Primas et al., in preparation). While this organic representation of the community is valuable, it may be interesting in the future to explore algorithms that ensure diversity among the reviewers assigned to each proposal. Achieving this would require a significantly larger pool of reviewers to balance these considerations effectively.

Implications and future directions

The successful integration of DPR into ESO's evaluation process demonstrates its viability as a scalable alternative to traditional panel reviews. The reduction in panel workload and the high satisfaction rates among users reinforce the value of DPR. Nonetheless, there is room for improvement:

- Adaptive Algorithms: ESO is exploring more sophisticated assignment algorithms, including those leveraging machine learning, to further enhance the match between proposals and reviewers.
- Keyword Refinement: Efforts are underway to make the keyword system more agile and reflective of contemporary science.
- Increased Feedback Participation: Strategies to improve the response rate for feedback surveys are being developed to expand the statistical basis for future analyses.

ESO plans to use DPR within its yearly proposal cycle, likely covering an even larger fraction of submissions to keep the expert panel load at the current level. While ALMA has implemented the DPR model for 100% of their submitted proposals, ESO plans to retain its panels for specific cases, such as joint ALMA–ESO proposals and those with significant time requests, ensuring a balanced approach that combines DPR's efficiency with the expertise of traditional committees[a]. Studies by Carpenter et al. (2022) on ALMA's implementation of DPR provide valuable insights that support these developments.

Expansion to fast-track channel

ESO is confident in deploying DPR for its upcoming fast-track channel, as highlighted by Patat et al. (2024). This channel is expected to streamline the evaluation on short timescales while maintaining the high standards of review quality established by DPR.

Conclusion

With DPR now operating across six periods, its benefits for the ESO community are clear. The process has reduced panel reviewer workloads, maintained fairness in proposal evaluations, and provided helpful feedback to PIs. The ongoing refinement of algorithms and reviewer profiling ensures that DPR will continue to serve as a model for peer review innovation in astronomy and beyond.

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Links

[1] ESO's DPR guidelines: https://www.eso.org/sci/observing/phase1/distributed-peer-review.html

Notes

[a] In the current implementation the proposals are split 50/50 in number, while the time share is 80/20 (Panels/DPR).

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ESO's Scientific Visitor Programme in Garching

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The ESO-Garching Scientific Visitor Programme invites astronomers and researchers from around the world to visit ESO in Garching for collaborative scientific activities. Open to scientists actively engaged in research, the programme promotes scientific interaction, innovation, and ESO's role as a hub of astronomical excellence. Visitors receive logistical and financial support, engage in ESO's vibrant scientific life, and contribute to its projects. Applications are reviewed by the Scientific Visitor Selection Committee. This programme aligns with ESO's mission to foster international collaboration in astronomy and its vision to work with and for the astronomy community.

Programme scope and objectives

The Scientific Visitor Programme at Garching[1] supports long-term visits by accomplished young and senior scientists, enabling close collaboration with ESO staff, fellows, and students. These visits, ranging from one month to a year (one to four months for Early Career Scientists[2]), provide researchers with the opportunity to engage with ESO's cutting-edge science, science operations and technology while contributing their expertise to foster innovation, promote scientific interaction and advance ESO's projects and goals.

Eligibility criteria

Eligible applicants for the regular visitor programme include scientists with a PhD in astronomy or related disciplines actively engaged in astronomical research. Early-career researchers (PhD students and postdocs up to three years post-PhD) are encouraged to apply via the Early-Career Visitor Programme[2]. All applicants must have an active affiliation and job contract during the visit.

While the programme is open to researchers of all nationalities, preference is given to citizens of ESO Member States, the host state Chile and ESO's strategic partner Australia. ESO is committed to diversity and inclusion, ensuring equal opportunities regardless of gender, age, disability, ethnicity or other factors.

Application process

Scientists interested in applying should complete the application form (available through the Visitor Programme web page) and submit it via email to the Visitor Selection Committee (VSC) Chairperson at vsc-chair@eso.org.

Applicants are encouraged to coordinate with an ESO staff member or Fellow before applying so as to align their visit with specific projects. Applications should be submitted at least four months prior to the planned visit to allow for practical arrangements. The programme's schedule tends to be busiest during the summer months (June–August), so visits outside this period are encouraged when possible.

Evaluation and selection

The VSC, comprising ESO Faculty members and Fellow representatives with diverse expertise, evaluates applications based on 1) scientific excellence, and 2) potential contribution to ESO's scientific projects. The committee meets about every two months to review applications and recommend candidates to the Head of the Office for Science.

Support and responsibilities of visitors

Approved visitors receive a monthly allowance for living expenses and family support, if applicable, reimbursement of travel costs, and accommodation in fully furnished ESO apartments, if available. They

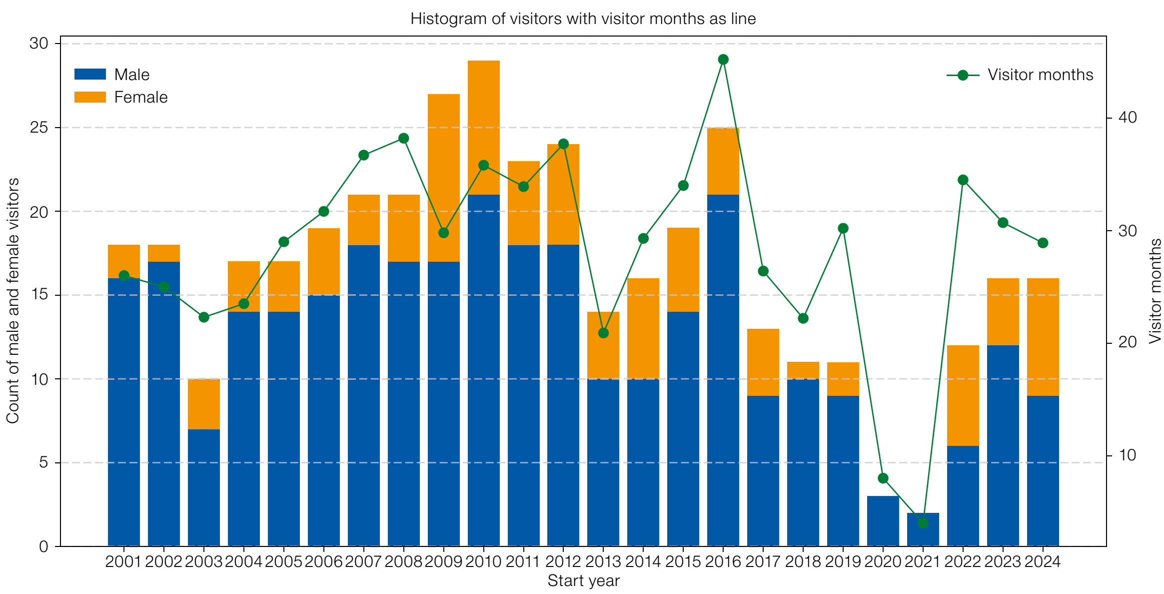

Figure 1. Number of male and female scientific visitors since 2001. The green line gives the number of visitor months accepted for each year (y-axis on the right). The effect of the pandemic in 2020/21 is clearly visible.

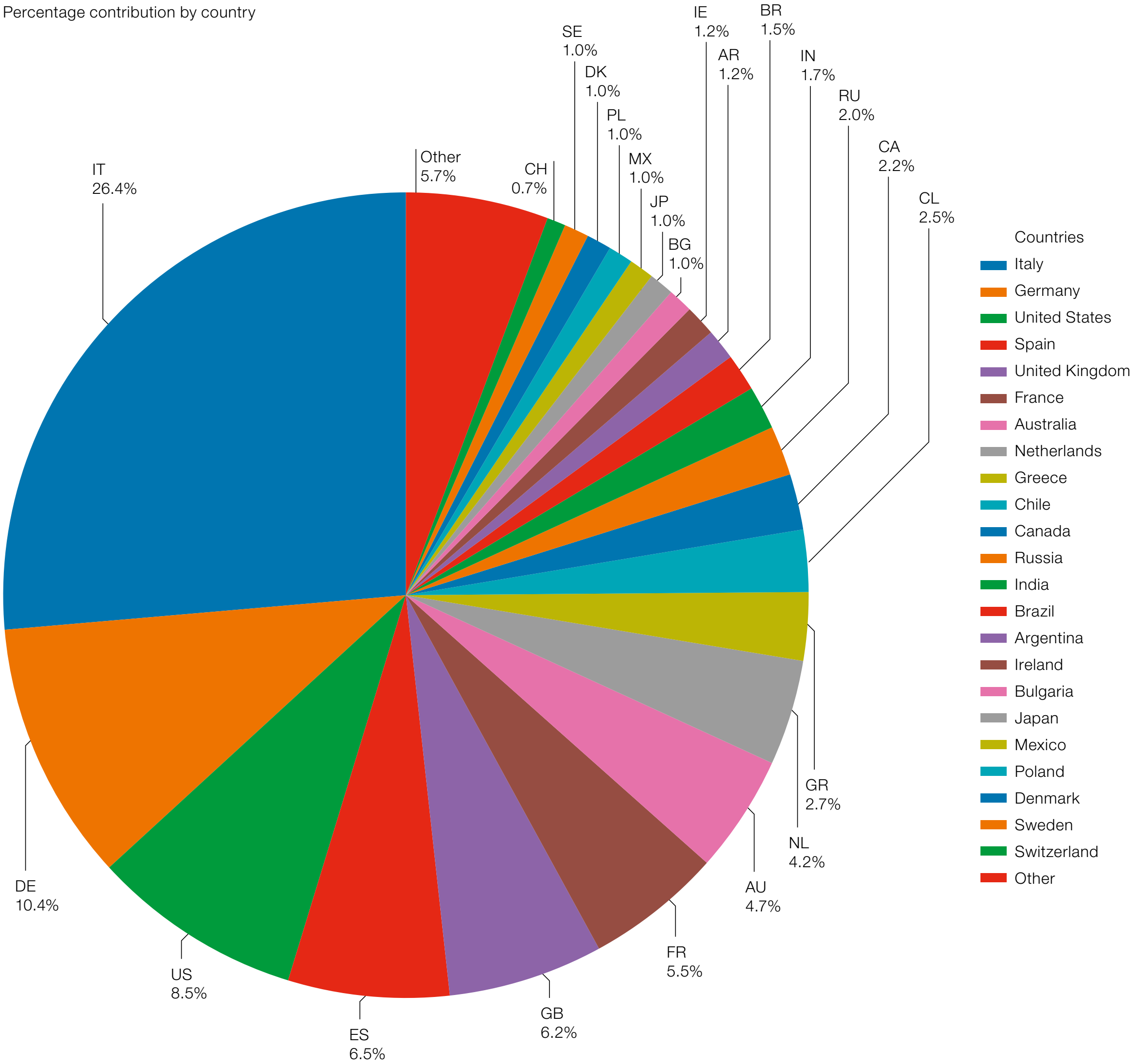

Figure 2. Pie chart showing the percentage contributions of visitors by country, with countries contributing less than 0.5% grouped into Others. More than a quarter of all visitors between 2001 and 2024 have Italian nationality.

are provided with office space, a computer terminal, and administrative support.

During their stay, visitors are expected to deliver a seminar or informal discussion, engage with ESO's scientific activities and adhere to the ESO Code of Conduct.

Some statistics on past visitors

For more than 30 years, ESO has been running a scientific visitor programme (see ESO, 1993). During this time, the Office for Science in Garching has hosted hundreds of visitors, comprising a mix of experienced, high-profile astronomers and early-career scientists. All have made significant contributions to ESO's scientific activities. They have delivered lecture series, talks and seminars, worked on white papers, and inspired ESO's young fellows and students. These interactions have sparked collaborations leading to successful observing proposals and refereed articles.

Figures 1 and 2 illustrate the demographics of scientific visitors since 2001. Over this period, the Office for Science in Garching has hosted 402 visitors, with annual numbers ranging from 10 to 29, except during the COVID-19 pandemic years. Visit durations have spanned the full range supported by the programme, with an average length of 1.7 months. On average, about 30 visitor months are approved each year, meaning that nearly three visitors are present at ESO at any given time.

Historically the proportion of female visitors was low (21.6% before 2022) but has improved in the past three years, reaching 38.6% thanks to increased awareness and training of the VSC and offered support.

References

ESO 1993, The Messenger, 72, 7

Links

[1] ESO's Scientific Visitor Programme: https://www.eso.org/sci/activities/garching/personnelvisitors.html
[2] Early-Career Scientific Visitor Programme: https://www.eso.org/sci/activities/garching/personnelvisitors/Policy_Early-Career_Scientific_Visitors_Garching.html

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Usage of Artificial Intelligence by ESO Telescope Users

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With the increasing integration of artificial intelligence (AI) and large language models (LLMs) into various fields, it is crucial to understand their capabilities and usage within the scientific community. This study explores the adoption and impact of these technologies among astronomers using ESO telescopes, specifically in the context of proposal preparation and review. We shared a survey with the ESO telescope users to investigate this further. We received 827 responses and found that around 20–30% of the participants use LLMs when preparing proposals and about 3% of the participants use them when reviewing proposals. We also found that there is a divide in how the usage of AI is perceived when proposals are prepared/reviewed, pointing to the need for ESO to establish clearer guidelines. These guidelines will be released for the next period.

Motivation for the survey and its outcome

Artificial intelligence (AI) is used commonly in all areas of science. A few years ago, the use of large language models (LLMs) in problem-solving tasks became relatively common by the release of ChatGPT and, following that, other similar conversational models such as Google Gemini and Claude. This has transformed the way that we approach research, coding, and potentially preparation for observing proposals. Therefore, it is important for ESO, as one of the forefront organisations in building and operating ground-based telescopes, to investigate the use of LLMs in proposal preparation and review, and, if necessary, establish policies regarding this. In this article, we report the results of a survey that we shared with the ESO telescope users to shed light on the current usage of AI in proposal preparation and review. This is part of the ongoing efforts at ESO (i.e., the STARS@ESO[a] working group; Jerabkova et al., 2024) to better understand the effect of AI on proposal preparation and review.

Survey demographics and AI usage

The survey on AI (in this context mostly LLMs) usage by the ESO community in writing proposals was open for around four and a half months. We contacted around 2300 PIs who had submitted a proposal in the last ten semesters and got 827 responses (about 36%). Figure 1a presents a summary of the career stages of the survey participants. The collected distribution and demographics are well representative of the ESO community. Figure 1a also shows how much experience the participants have had of writing proposals. In brief, 55% of the survey participants have faculty positions, 30% are postdoctoral researchers, and 15% are PhD students. Faculty members mostly have more than five years of experience and PhD students mostly have one to two years of experience of writing proposals.

Of the survey participants only about 23% use AI to draft proposals. The usage of AI also correlates with level of seniority, with 33% of PhD students, 27% of postdoctoral researchers, and 18% of faculties using AI when writing proposals. This is illustrated in Figure 1b. Although a smaller portion of the faculty members seem to use LLMs in proposal preparation, given their larger group size it still results in a larger number of faculty members using AI than postdoctoral researchers or PhD students. Of those who use AI (about 190 participants), most did not notice any change in their success rate. More specifically, Figure 1c shows that only around 10% of the participants who use AI across various career stages noticed a positive change in their success rate.

We were also curious about how LLMs are used when drafting proposals. The left panel of Figure 2 shows a summary of what AI is used for. Across career levels, it is mostly used to enhance clarity and readability. After that, it is mainly used for the title of the proposal. Finally, a minority use AI for fact checking, for calculations, and/or for writing an entire abstract. Two participants mentioned that they use AI for writing the entire proposal including suggestions for the science idea. When it comes to reviewing proposals, the right panel of Figure 2 shows that most participants (~97%) do not use AI for this purpose. However, around 3% do use AI when reviewing proposals, which accounts for around 28 of the participants.

Relevant comments

We also asked the participants to provide any relevant comments. From those who provided them, two main general themes emerged. Around 80–90 participants (~10%) expressed their concern regarding the use of LLMs in either preparing the proposals or reviewing them. Some went as far as suggesting banning its use altogether or implementing a procedure to catch those who use LLMs for the

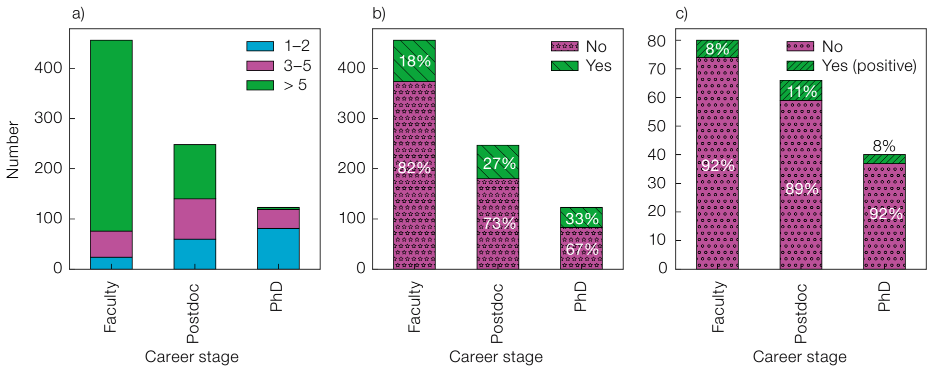

Figure 1. a) Number of participants in different career stages; the colours present the number of cycles for which they have written a proposal for ESO telescopes. b) The result of their answers to the question: Do you use AI when preparing proposals? c) The result of their answers to the question: If you use AI for proposals, have you noticed any change in your success rate?

proposal preparation and disqualify those who use it above a certain threshold. On the other hand, some of those who were concerned did not object to its use in improving the language of the proposal, especially for those who are not native speakers of English. Some of the concerns were related to the ethical aspect, as the large language models (LLMs) are trained on what is the intellectual property of others and therefore proper citations are required; the words “unethical” and “plagiarism” were used in several comments. Another concern that a few participants expressed was related to the decline of creativity and the uniformity of all proposals when using such models. Several participants also pointed to the need to double check what a LLM produces to avoid wrong statements. One person suggested that a negative factor could be the use of AI to make the proposal sound interesting, which may appeal to the younger reviewers, while the proposal may have scientific issues. A few people were also concerned about the energy consumption and carbon dioxide emission when training the LLMs. Some of those with concerns about the use of AI in reviewing proposals particularly mentioned the issue of consent, potentially hinting at the need to have the PIs’ agreement for their proposals to be uploaded into LLMs. Some were also suspicious that they received reviewer comments generated by AI and that they were generic and not quantitative. One person was worried that the distributed peer review process might lose its meaning if AI is used in reviewing proposals.

The second theme included participants who were more positive about using LLMs in the preparation of proposals or reviewing them. This group consisted of around 60 participants (~7%) with roughly half of them emphasising the potential of AI in helping non-native speakers of English to produce higher quality text, which can increase the fairness of the process. This more positive group also included participants who are thinking about starting to use AI in proposal preparation and/or review in the future. One person even suggested integrating it into the proposal tool. Another person noted that in the review process, LLMs might have fewer issues with personal conflicts but it has also been suggested that AI may be more

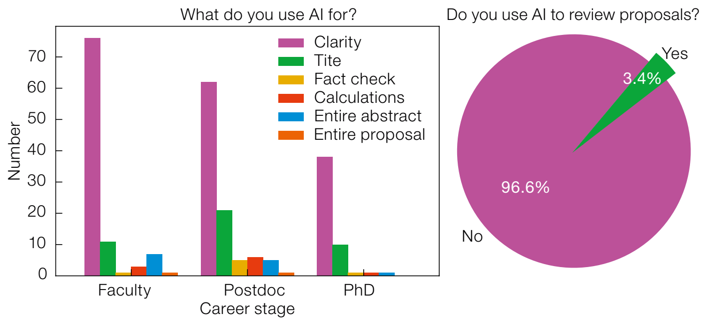

Figure 2. Left: This plot shows what AI is used for when preparing proposals. Right: The portion of the participants who use AI for reviewing proposals.

in favour of proposals written by LLMs (Jerabkova et al., 2024). Although some participants in the other group were worried about declining creativity, one person in this more positive group mentioned the use of AI for inspiration.

Other comments included suggestions to assess proposals in a different way if LLMs are to be used more widely, for example by putting less emphasis on the clarity of the proposals and more on the science idea. A few participants suggested asking for a disclaimer from proposers/reviewers to confirm whether LLMs are used to produce/review proposals. Finally, we also received comments on the shortcomings of our survey. For example, some participants indicated that they use LLMs for coding and making plots, which was not given as an option in the survey. As we wanted to keep the survey short, we avoided asking more in-depth questions on the exact usage of LLMs when reviewing proposals. Therefore, a few participants elaborated on their usage when reviewing the proposals. These included asking AI questions on a subject to learn a topic fast enough to be able to assess the proposals fairly and using LLMs to refine and increase the clarity of their comments.

Closing remarks

To conclude, around 20–30% of the survey participants already use LLMs in the proposal preparation process and there seems to be a divide between those who strictly disagree with the usage of LLMs in proposal preparation and those who are more positive about it and see potential benefits. These findings indicate that ESO likely needs to establish a policy on whether LLMs are allowed to be used in the proposal preparation and review process and, if so, to what extent they can be employed. Currently, ESO only has a disclaimer at the start of the review process such that the reviewers agree to not share the proposals with third parties. With the implementation of the new Confidentiality Agreement for the Review of the ESO Observing Proposals, stricter measures are now in place to safeguard sensitive information. Reviewers are explicitly prohibited from using automated processing methods, including AI tools such as ChatGPT, Google Gemini, or Claude, to process, analyse or interpret proposal content without prior written consent from ESO. This agreement ensures that confidential information remains secure and emphasises the importance of maintaining integrity and authenticity in the review process. As we move forward in this rapidly evolving technological landscape, ESO acknowledges the need for further specific guidelines and policies to address the ethical and practical challenges associated with AI usage in proposal preparation and review.

Acknowledgements

We thank the ESO Director for Science for supporting this research. Moreover, we thank all the ESO telescope users who participated in the survey. PN acknowledges support from the ESO and IAU Gruber Foundation Fellowship programmes.

References

Jerabkova, T. et al. 2024, arXiv: 2407.02992

Notes

[a] STARS stands for Scientific Text Analysis with RobotS

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Report on the ESO workshop

The Promises and Challenges of the ALMA Wideband Sensitivity Upgrade

held at ESO Headquarters, Garching, Germany, 24–28 June 2024

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The Atacama Large Millimeter/submillimeter Array (ALMA) is undergoing the most ambitious project since its inauguration: the Wideband Sensitivity Upgrade (WSU). The WSU will increase the instantaneous bandwidth by as much as a factor of four while retaining full spectral resolution over the entire bandwidth, thus resulting in increases of the spectral scan speed of up to a factor of 50 for the highest spectral resolution. In addition, an upgrade of the full signal chain of ALMA — from the receivers and digitisers all the way through to the correlated data — will result in increases in sensitivity for all observations. However, the increased bandwidth and throughput bring several technical challenges. In June 2024, we organised the first conference at ESO in Garching to inform the ALMA community about all the details of this upgrade. Here we report on the outcome of this meeting.

Motivation

In its first decade, the Atacama Large Millimeter/submillimeter Array (ALMA) has revolutionised our view of the Universe, both near and far (see Díaz Trigo et al., 2024). Serving a very broad range of science topics has been one of the main successes of ALMA, leading to a sustained high demand from the scientific community. Being the most powerful (sub)mm observatory in the world also comes with the responsibility to continuously fulfill the high expectations of the community. While ALMA set new standards in (sub)mm technology during construction, other observatories such as the Northern Extended Millimetre Array (NOEMA) and the Submillimeter Array (SMA) now offer an instantaneous bandwidth coverage wider than ALMA's. Indeed, expanding that bandwidth was set as the top priority of the ALMA2030 roadmap (Carpenter et al., 2020), and the Wideband Sensitivity Upgrade (WSU) is the response to that goal. The WSU2024 conference was the first time the entire ALMA user community was informed in detail of the broad scope of the WSU. While many of the technical upgrades within the WSU are intrinsically linked to each other (for example, digitisers, digital signal transport and correlator), others are relatively independent (for example, receiver upgrades, data reduction software). Therefore, having scientific input from the community to help set the priorities within the WSU project was a second goal of the meeting.

The conference brought together the scientific and technical user communities, while also covering a broad range within these communities. For example, the science topics covered the Sun, the Solar System, protoplanetary discs, stars, astrochemistry, the interstellar medium, nearby and distant galaxies, galaxy clusters, cosmology and special observing modes such as time domain, polarisation and very long baseline interferometry. The technical topics covered the whole ALMA signal chain from receivers and their components, digitisers and correlator, to the impact of the WSU on ALMA operational aspects such as user support, quality control, data processing software tools and the archive. The presentations are available on Zenodo[1].

Interaction between science and technology

Fostering interaction between science and technology during a conference is a challenging task, and has been attempted at several previous meetings, when these different topics were often clearly separated in the programme. Unfortunately, this leads to many participants attending only the session(s) in their own field, which does not stimulate interaction between the groups. We therefore attempted a new structure in the programme[2], mixing technical and scientific talks within the same session. To retain coherence, we did keep a focused technical and scientific topic within each session. Each half-day was then concluded with a one-hour discussion on a topic relevant to both the preceding scientific and technical talks. To further stimulate engagement of the participants, we organised quick online polls using Mentimeter, which also allows online participants to be actively involved. While these polls obviously do not pretend to offer a representative opinion of the whole ALMA user community, they did help to streamline the discussion and to provide some guidance about community priorities for the WSU (see below).

One positive outcome of these interactions between technical and scientific groups was a lively discussion of how ALMA users can help increase the visibility of instrument builders. For example, encouraging astronomers to cite the relevant instrument papers in their scientific papers can help obtain funding for new receiver development. Facilitating access to instrument papers in the SAO Astrophysics Data System, making accessible to users a list of relevant technical papers[3] or updating the ALMA citation policy were discussed in this context.

Wideband and sensitivity upgrades

The overarching goal of the meeting was to present in detail the improvements the WSU will bring to ALMA users. To enable the wider bandwidth and increase the digitisation efficiency, ALMA will first need a completely new signal chain. The signal chain will include new digitisers in all the ALMA antennas, which will allow any intermediate frequency (IF) in the range 2–20 GHz to be covered, providing a flexible system to serve the upgraded receivers. A new digital signal transport system will carry the signal to the Operations Support Facility (OSF), where the Advanced Technology ALMA Correlator (ATAC) will be installed to offer spectral resolutions of 0.1 km s^{-1} or better over the entire correlated bandwidth, so that ALMA users no longer have to sacrifice bandwidth for spectral resolution. Even before upgrading the receivers, the new digitisers and the ATAC will already offer an increase of spectral grasp and a sensitivity improvement of more than 10%.

When combined with ALMA's high spatial resolution, the WSU will allow much more powerful studies of astrochemistry in a wide variety of targets including comets, protoplanetary discs, prestellar cores and (high-mass) protostars, star-forming regions, and nearby galaxies. Several speakers highlighted the formidable

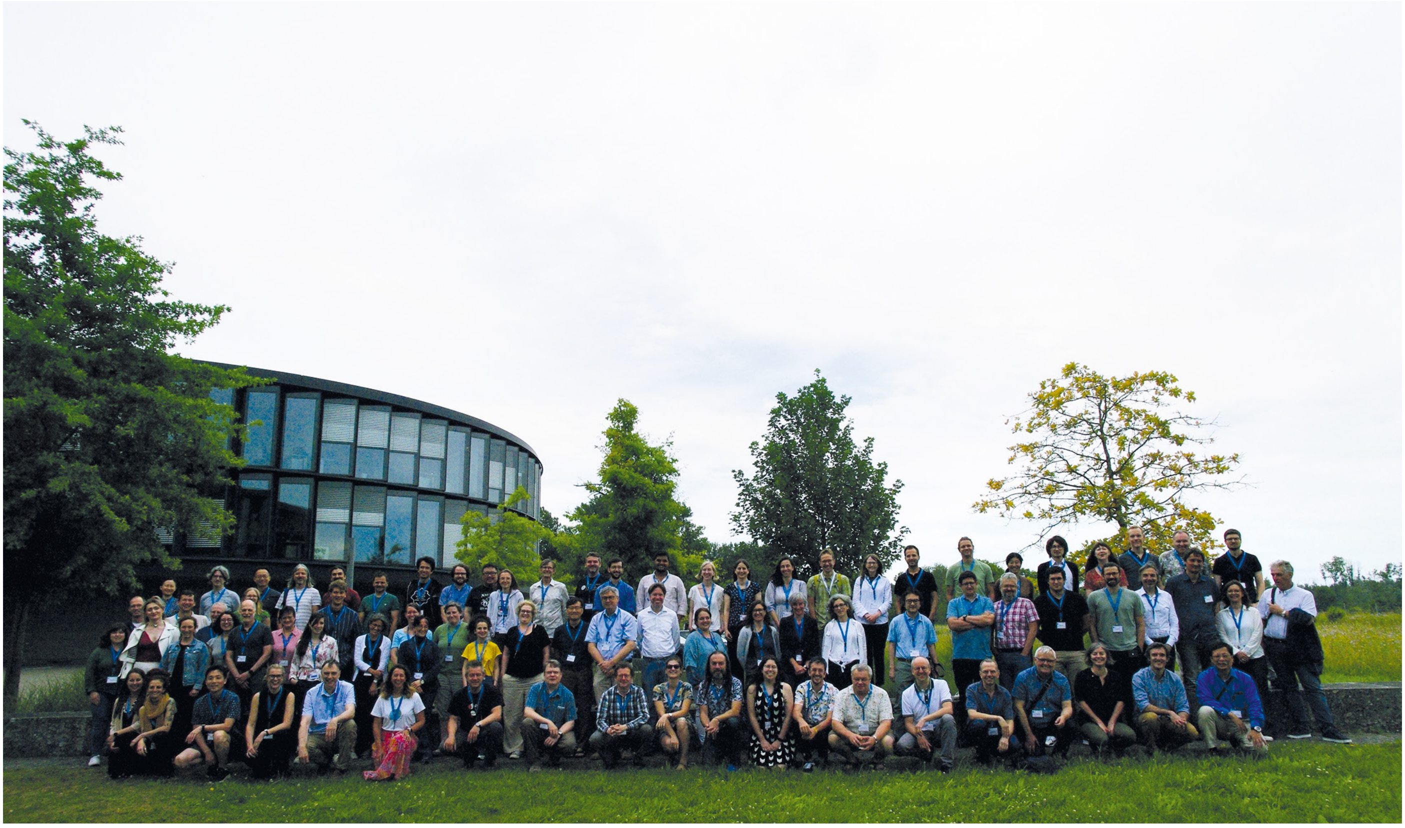

Figure 1. Conference photo.

challenge that awaits them in modelling WSU datasets containing thousands of molecular lines. Results from several ALMA Large Programmes presented at the meeting already gave a first glimpse of what to expect from WSU datasets, showing that we are already at the limit of what astronomers can handle with the current analysis tools. With the WSU, these datasets will increase by at least an order of magnitude. Significant upgrades of the spectral fitting and chemical analysis tools are already starting, and will require the incorporation of machine learning techniques.

The promise of the WSU is to increase the instantaneous bandwidth by at least a factor of two, the goal being a factor of four (i.e., 16 GHz per sideband and per polarisation). Reaching this goal of a factor of four came out as a clear priority from the quick poll of the participants (see Figure 2). The benefits of the broadest possible bandwidth are obvious for spectral line surveys (both Galactic and extragalactic, such as redshift surveys), where broader bandwidth provides not only a commensurate gain in observing time, but also more uniform data over a wide spectral range, thereby increasing their archival value. For sources with a lower density of spectral lines, a broader bandwidth also increases the flexibility in the spectral setup. Several speakers highlighted the importance of such more efficient spectral setups, for example for time-critical or time-intensive observations of variable sources or polarisation measurements, for which the use of subarrays was also suggested as a way to further increase the simultaneous broad bandwidth. The factor of four increase in bandwidth will result in an improvement of the sensitivity and calibration accuracy, which is important for, for example, accurate spectral slope determinations.

While the ATAC ingest has been designed to record up to four times the current bandwidth, reaching this full capacity will require additional hardware investments. Reaching bandwidths of 16 GHz is also a challenge for the receivers being upgraded. Some receiver components such as the optics, corrugated horns and lenses or cryostat entrance windows may not need upgrades, while others such as the cryogenic low-noise amplifiers already have prototypes covering IF bandwidths from 4 to 20 GHz which would meet the WSU requirements. Improving in areas such as the polarisation accuracy may come with a penalty on sensitivity, which could be alleviated by reducing waveguide losses using new fabrication technologies.

The receiver upgrades presented for Bands 6, 7, 8, 9 and 10 are all planning to use silicon-insulator-silicon technology, where the most challenging part is to combine a bandwidth four times broader with tighter requirements on the receiver temperature and sideband rejection. The new Band 2 receiver (extending over the existing Band 3 range) instead uses a low-noise amplifier as the first active component (see Figure 3). Band 2 is both the last of the originally planned ALMA receivers, and also the first receiver that

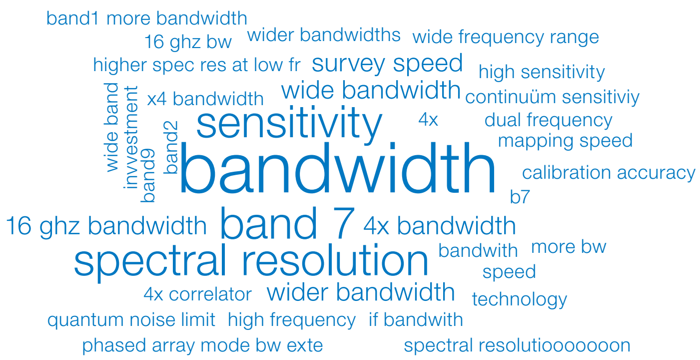

Figure 2. Results from a quick poll of the conference participants to gauge their main priority for the WSU.

is compatible with the new WSU requirements. As the ongoing installation of the Band 2 production receivers should be completed by the time the ATAC, digitisers and digital signal chain are being installed, Band 2 will be a critical band for the WSU commissioning.

During the discussion sessions of the WSU2024 conference, there was constructive input from ALMA users on the timeline of the upgraded receivers. With the upgrade projects for Bands 6 and 8 already started, the participants expressed a clear preference for Band 7 to be the next priority, consistent with the priorities originally set in the ALMA2030 roadmap. Interestingly, the conference participants appeared to be willing to compromise on the schedule or even forego the last GHz of bandwidth to see this important band upgraded. After band 7, most participants preferred to upgrade band 9 before bands 1, 4+5 and 10.

Impact on ALMA users

As previously mentioned, the increased spectral grasp and bandwidth of ALMA in the WSU era will lead to substantially increased data volumes. While the median increase in the product size is expected to be less than an order of magnitude, some products will be more than three orders of magnitude larger. This will require the replacement of the current ALMA data reduction software, the Common Analysis Software Applications (CASA), by a new suite named the Radio Astronomy Data Processing System (RADPS). The WSU2024 conference also had a session dedicated to collecting new ideas and user requirements for the ALMA archive in the WSU era. It became clear that there is a strong desire to execute more of the processing steps on servers hosting the data, especially for ALMA users who do not have access to powerful computing facilities. In addition, machine learning techniques may help to alleviate the formidable challenges of the WSU data volumes.

A major upgrade like the WSU will not come without some sacrifices by the ALMA users. A mitigation plan to reduce the operational downtime during the upgrade was presented during the meeting. For example, during the commissioning of the initial WSU, the new signal chain will operate in parallel to the existing one. With the diversity of the ALMA user community represented during the WSU2024 conference, it became clear that it is impossible to find a strategy that will satisfy all users. For example, during the most intense WSU commissioning phase, a reduced number of antennas and time will be available for science observations, and some observing modes or configurations may not be offered. The alternative of a prolonged shutdown period, or even skipping a full Cycle, was not considered as attractive by most of the conference participants.

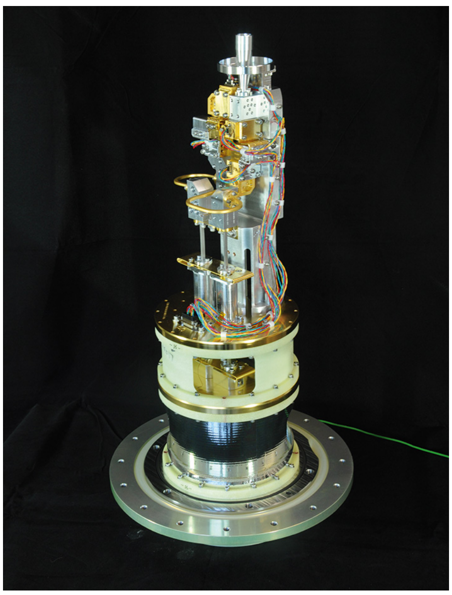

Figure 3. The ESO-led Band 2 receiver will be the first ALMA receiver compatible with the WSU requirements, covering an IF bandwidth from 2 to 18 GHz.

Demographics

The Scientific Organising Committee (SOC) included representatives from all the ALMA Regional Centre nodes as well as ESO ALMA staff and the ALMA observatory scientist. To ensure a representation from a wide range of scientific and technical fields, the SOC invited 27 speakers. Both the SOC and invited speakers had a 44% female participation. The total number of registered participants was 152, of whom 110 attended in person and 42 remotely. The overall female participation percentage was 39%, which could reflect the lower female fraction in technical staff positions. Although the SOC tried to attract more early-career scientists by offering a reduced registration fee, only 28% were students or postdocs. While the meeting primarily targeted European users, 30 participants from North America, East Asia and Chile also participated.

Acknowledgements

We thank the Scientific and the Local Organising Committee for their extensive and efficient help in making this conference a success.

References

Carpenter, J. et al. 2020, arXiv:2001.11076
Díaz Trigo, M. et al. 2024, The Messenger, 193, 57

Links

[1] Zenodo link to the presentations: https://zenodo.org/communities/alma-wsu-2024
[2] Link to workshop page: https://www.eso.org/sci/meetings/2024/wsu.html
[3] ALMA technical handbook: https://almascience.eso.org/proposing/technical-handbook

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Report on the ESO workshop

Galaxies at Crossroads: Outflows and IMF in the VLT/ELT/ALMA/JWST Era

held at Brno Observatory and Planetarium, Czech Republic, 16–20 September 2024

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The international workshop Galaxies at Crossroads gathered a diverse group of researchers to address pivotal themes in galaxy evolution, including galactic outflows, the stellar initial mass function, and the mass-metallicity relation. Hosted in collaboration with Masaryk University, the event featured a robust scientific programme complemented by interactive activities, emphasising collaboration and fostering early-career participation. The location in Brno, close to the University of Vienna and the Institute of Science and Technology Austria, provided an ideal and sustainable meeting point in central Europe, easily accessible by train. This report highlights the science, the participant statistics, and how effective it can be when workshops are organised outside of ESO to foster stronger interactions between the community and ESO.

Motivations

The workshop was driven by the need to address pressing questions in galaxy evolution from different angles and to foster collaboration across different extragalactic research domains. ESO's strategic focus on supporting Member States and strengthening regional scientific communities was central to its objectives.

A major theme of the meeting was bringing together experts on three interconnected yet expansive topics: galactic outflows, the stellar initial mass function (IMF), and chemical evolution. Each of

Brno Planetarium

Figure 1. Conference photo.

these areas is often the focus of separate conferences, but this workshop sought to foster interactions among experts across these fields. A particular emphasis was placed on bridging observational and theoretical perspectives, uniting observers, simulators, and theorists to encourage cross-disciplinary dialogue.

Additionally, the workshop aimed to enhance engagement in the central Europe region, which hosts rapidly growing research institutes, and to strengthen ties with ESO and ALMA science. Brno, strategically located between the capital cities Prague and Vienna, served as an accessible and sustainable venue, reinforcing ESO's commitment to supporting research in Member States.

Summaries of talks and highlights from sessions

A major theme of the meeting was to set the stage for collaborative discussions across fields that are often tackled independently. The programme[1] included:

- Setting the Scene: the workshop opened with an overview of active galactic nuclei (AGN) and the Czech Space Telescope QUVIK, presented by Michal Zajacek, followed by Pavel Jachym's update on ALMA science, Czech ALMA Node activities, and jellyfish galaxies. Participant introductions fostered by noughts-and-crosses-style activities (a variation of bingo, which proved to be a great success) during the welcome drinks reception created an engaging atmosphere for networking. The goal was to create an environment in which it was easy to engage with new people, ensuring that participants from three different astronomy fields had the opportunity to connect beyond their usual circles.
- Galactic Outflows: the second day began with Barbara Mazzilli Ciraulo's highlight talk on cold outflow filaments in Generalising Edge-on galaxies and their Chemical bimodalities, Kinematics and Outflows out to Solar environments (GECKOS) winds, followed by Alejandro Olvera's exploration of gas flows in NGC 99. Other highlights included Bronwyn Reichardt Chu's discussion of star formation-driven outflows and Archana Aravindan's focus on AGN-driven outflows in dwarf galaxies. An invited talk by Jorryt Matthee presented future prospects for spectroscopic observations of galaxies in the first Gyr, followed by group discussions led by Filipo Fraternali, Antonino Marasco, Ivanna Langan, Bronwyn Reichardt Chu, and Matej Barta.
- Initial Mass Function (IMF): day three featured invited talks by Zhiqiang Yan on chemical tracers for constraining the IMF and Alina Boeker on observational and simulation-based IMF studies. Highlights included Ankur Upadhyaya's evidence for very massive stars in UV-bright galaxies and Prasad Sawant's unveiling of baryon cycles in $z \sim 5$ galaxies. The discussion session was organised by Ignacio Martin Navarro, Marie Zinnkann, Andrew Hopkins, and Glenn van de Ven, fostering interaction between theorists and observers.
- Mass-Metallicity Relation (MZR): the fourth day began with keynote speaker Allison Strom, who re-examined metallicity through chemical abundance patterns in distant galaxies. Additional highlights included Dirk Scholte's analysis of transitions in the baryon cycle and Gauri Kotiwale's work on galaxy metallicity at the epoch of reionisation. Discussions were facilitated by Belen Alcalde, Zhuang Zhuyun, Gauri Kotiwale, and Ivanna Langan, focusing on integrating observational and theoretical perspectives.
- Final Day Discussions: the workshop concluded with X-ray astrophysics highlights, including talks by Julia Falcone on Seyfert galaxy feedback and Michal Zajacek on ultrafast outflows. Norbert Werner introduced high-energy astrophysics research being conducted at Masaryk University. This was followed by a short wrap-up discussion involving the Scientific Organising Committee and participants, and a planetarium show highlighting synergies between high-energy astrophysics and galaxy evolution research.

Interactive and collaborative activities

The workshop was designed to ensure active engagement and discussions:

- Session Structure: sessions were carefully timed to allow a focus on each presentation, with sufficient breaks to prevent fatigue. This 'light' programme gave participants time to properly digest the talks and engage in meaningful discussions during the breaks and dedicated discussion sessions. The use of different talk lengths — from longer keynote presentations to concise five-minute contributed talks — helped strike a balance between giving space to key topics and allowing more contributors to present their work. In particular, the concise talks proved effective for conveying key science messages and essential details. This approach was inspired by the Lorentz Center workshop "Gravitational waves: a new ear on the chemistry of galaxies" (29 April – 3 May 2024)[2] which demonstrated the value of varying talk formats to maintain engagement while maximising impact. Unlike programmes packed with numerous talks, which can leave attendees drained and skipping sessions, this structure encouraged full participation. It was fantastic to see that everyone stayed engaged throughout, creating a vibrant atmosphere for experts from varied fields to interact and collaborate effectively.
- Discussion Sessions: each scientific topic was paired with a dedicated discussion session. Participants were divided into groups based on career stage and expertise to ensure balanced representation, while other discussions involved all attendees using online tools for real-time voting and comments.
- Group Summaries: after group discussions, joint sessions were held, with early-career researchers bravely presenting their group's findings, fostering inclusivity and confidence.

Main conclusions and ways forward

The workshop achieved its goals of fostering collaborations and advancing discussions on galaxy evolution. Plans to build synergies across related fields were emphasised, as this approach is essential for understanding the full picture, particularly in the context of growing synergies between facilities, such as the JWST, the Atacama Large Millimeter/submillimeter Array, and ESO's upcoming Extremely Large Telescope (ELT). Strengthened networks among early-career researchers were another significant outcome, with mentorship opportunities fostering

T. Jerabkova

Figure 2. This image is from a sneak preview we received of the exhibition prepared by the Brno Planetarium staff, showcasing their exceptional work and support during the workshop.

inclusivity and development. It was particularly rewarding to witness exceptional collaboration across fields and between early-career and senior scientists. The group dynamics were notably enriched by diverse discussion formats, including small group splits and online tools that allowed anonymised audience input in real time. Additionally, the event fostered new connections between Czech and Austrian institutes, laying the groundwork for future collaborations. Recorded talks and presentations are available on YouTube[3], and are accessible on Zenodo[4]. This workshop exemplifies the potential for similar collaborative efforts, especially in preparation for the ELT and other next-generation observatories.

Demographics

The Scientific Organising Committee sought fair representation from the community. Invited speakers were selected to represent a balance of career stages and scientific expertise. The final programme included 47% female and non-binary participation, aligning with the proportion of female and non-binary participants at the workshop. Additionally, over 70% of attendees were students and postdoctoral researchers, reflecting ESO’s emphasis on fostering the next generation of astronomers. Early-career researchers also contributed as session chairs and discussion leaders, showcasing their leadership potential.

Participants (Figure 1) came from over 20 countries, with notable contributions from ESO Member States and partner institutions. The breakdown of participants by region was:

- 65% from Europe (notably Germany, Italy, Czech Republic, Austria, France, and Spain),
- 15% from North America (USA and Canada),
- 10% from Asia (including China and India),
- 5% from South America (notably Chile and Brazil), and
- 5% from Australia.

The distribution highlights strong engagement from European institutions, with a growing presence from North America and Asia, reflecting the international appeal of the workshop. To further promote inclusivity, pronoun stickers were introduced, allowing participants to display their preferred pronouns on their badges. This initiative, which aimed to create a welcoming environment for all attendees, has since been adopted by other ESO workshops, underscoring its positive impact.

Acknowledgements

The organising committee extends its gratitude to ESO for funding and workshop support, and to the ESO Workshop Selection Committee for endorsing this event. Special thanks go to the Planetarium in Brno[5] for providing an exceptional venue and outstanding technical assistance, which were critical to the workshop’s success (Figure 2). The event also benefitted greatly from the contributions of local students, postdocs, and staff members who provided invaluable support with the organisation. We acknowledge Masaryk University for its collaborative efforts in hosting the workshop. Finally we thank all participants for their inspiring attitude and openness to collaborations and we thank all invited speakers.

Links

1. Link to workshop programme: https://www.eso.org/sci/meetings/2024/galcross/programme.html
2. Lorenz Center Workshop: https://www.lorentzcenter.nl/gravitational-waves-a-new-ear-on-the-chemistry-of-galaxies.html
3. Recorded presentations: https://www.youtube.com/playlist?list=PL-7vLpk0VDrlLpaZsWQNntDLVmHav1G7U
4. Presentations on Zenodo: https://zenodo.org/communities/galcross2024/records?q=&l=list&p=1&s=10&sort=newest
5. Brno Planetarium webpage: https://www.hvezdarna.cz/en/

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Report on the ESO workshop

New Heights In Planet Formation

held at ESO Headquarters, Garching, Germany, 15–19 July 2024

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[1] ESO

Planet formation is a widespread by-product of the process of star formation itself and occurs within protostellar discs made of gas and dust that orbit the newborn star. In the past few years new observations of discs at various wavelengths — thanks to new-generation facilities — have revolutionised the field of planet formation and challenged some of the traditional theories. This workshop brought together around 200 scientists from all over the World to review the state of the art, pinpoint the main open questions, and explore new avenues. As well as invited reviews and talks, and contributed talks, the scientific programme offered ample space for informal poster viewing sessions.

Rationale

Planet-forming discs can nowadays be probed in unprecedented detail thanks to facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA) at submillimetre wavelengths or high-contrast imaging instruments in the near-infrared, such as the Spectro-Polarimetric High-contrast REsearch (SPHERE) instrument at ESO's Very large Telescope. In the past decade these facilities have transformed the field of planet formation, enabling both moderate-resolution statistical disc surveys and high-resolution imaging studies of discs. Improvements in data quality and sample size have, however, raised many fundamental questions about the structure of discs and their evolution, all the way to the formation of planets. This observation-driven field seems to be continuing along this path with upcoming results from the James Webb Space Telescope (JWST) and the many recently accepted Large Programmes that are ongoing at different facilities. Theory and models are therefore faced with the task of explaining much more complex scenarios of disc evolution, planet formation, and planet–disc interaction.

This workshop aimed to bring together observers with expertise in different wavelength regimes, theorists, and modellers to evaluate our current progress, pinpoint critical unresolved challenges, and discuss ways forward.

Programme

Several topics were addressed during the ESO workshop. We started with a beautiful and extensive review of recent JWST results in the context of planet-forming discs, with a special focus on the level of improvement compared to its predecessors. This set the stage for a

Figure 1. Conference photo.

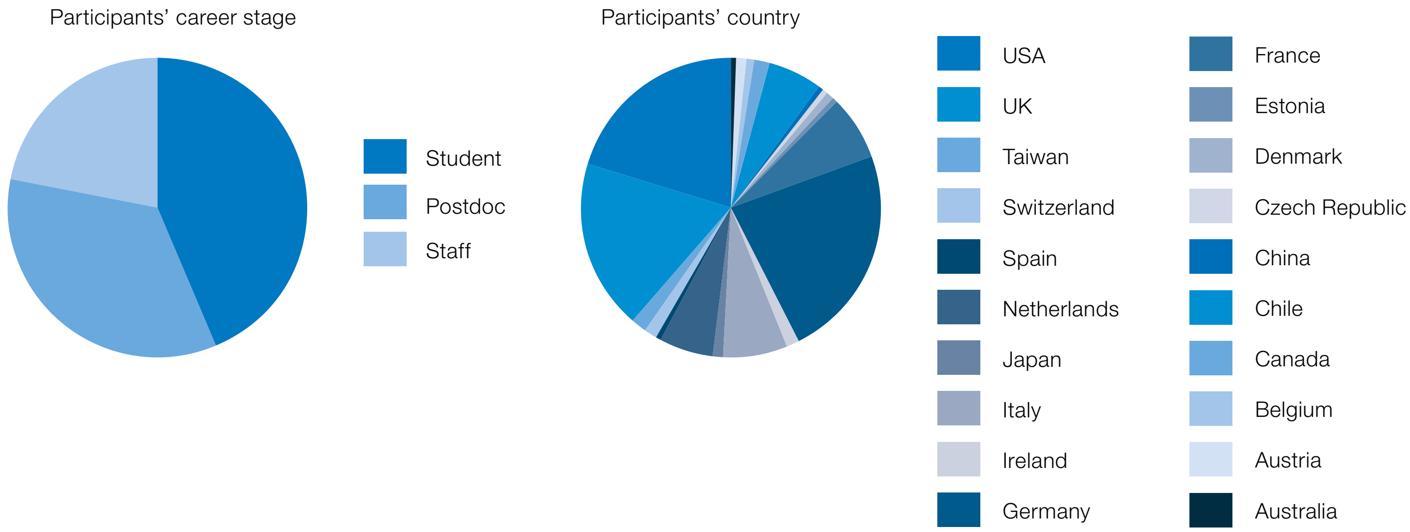

Figure 2. Demographics.

series of novel JWST results highlighted in both contributed talks and posters. The second day was devoted to the enormous contribution of ALMA to our understanding of discs. Some results from two of the recently accepted ALMA Large Programmes (AGE-PRO and Exo-ALMA) were presented, addressing the fundamental yet unsolved problem of disc evolution and the prospects of detecting embedded protoplanets using disc kinematics. The third day was mostly devoted to theory and simulations with a special focus on planet–disc interaction. On the fourth day we addressed the effects of the environment on discs. That topic was possibly the one that generated most interest and stimulated most of the discussion. Recent results, in fact, have shown that external processes may be very relevant in discs even at later stages while planets are forming. Finally, on the last day, the topic of astrochemistry was addressed and new advances in this area thanks to the recently accepted ALMA Large Programme DECO were presented.

The programme included 67 talks over five days, including seven invited review talks and five invited talks, the remainder being contributed talks selected by the Scientific Organising Committee (SOC). For the five invited talks the SOC selected junior members of the main five Large Programmes ongoing in the field of planet formation. We also held one open discussion session. As well as the oral contributions, 75 posters were presented, divided into two poster sessions in the first and second halves of the week. The SOC decided to give more visibility to some of the outstanding results presented on posters by rewarding the three best posters with a five-minute talk on the last day of the conference. Two of the best posters were selected by a committee and the third one was voted by the conference participants through a web poll.

Demographics

The workshop was co-funded by the DUSTBUSTERS[1] collaboration on protoplanetary discs, funded by an EU Marie Skłodowska Curie RISE grant. It was timed to serve as the closing event of DUSTBUSTERS. The SOC consisted of DUSTBUSTERS node leaders and external scientists, four female and five male members, with nine SOC members from seven countries (Australia, Italy, Chile, USA, France, UK, Germany). Our final numbers included 267 registered participants, of whom 186 were in person, from more than 20 different countries.

The SOC made every effort to ensure a balanced scientific programme, with 27 of 67 speakers (~40%) being female. Likewise, the priority was to support and give visibility to early-stage researchers (ESRs) in selecting both invited speakers and contributed talks. In fact, 55 of 67 speakers (~82%) were either PhD students or postdocs.

Outlook

The workshop was the major scientific event in the field of protoplanetary discs in 2024. Feedback from the participants was very positive. The efforts to give visibility to ESRs was much appreciated, as was the friendly atmosphere, which allowed interesting and respectful interactions and discussions. Despite the large number of participants, reaching the limits of the ESO capacity, the organisation was very smooth, mostly thanks by the numerous and engaged Local Organising Committee (LOC), composed of 12 ESO students, fellows and staff members.

Slides from most talks, the detailed programme, the list of posters, and the LOC/SOC composition are available at the workshop website[2].

Acknowledgements

We would like to thank all participants, both in person and remote, for their active participation in the conference, which was crucial to making it such a success. We would further like to thank our SOC and LOC members for their fundamental and invaluable effort. A special thanks goes to Denisa Tako for her support with the organisational aspects of the conference.

Links

[1] Link to the DUSTBUSTERS Webage: https://dustbusters.fisica.unimi.it/

[2] Link to workshop programme: https://www.eso.org/sci/meetings/2024/dustbusters.html

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Report on the ESO workshop

A Decade of Discoveries with MUSE and Beyond

held at ESO Headquarters, Garching, Germany, 18–22 November 2024

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Joël Vernet[1]
Pascale Hibon[1]
Amelia Fraser-McKelvie[1]
Ashley Barnes[1]

[1] ESO

The Multi Unit Spectroscopic Explorer (MUSE) spectrograph is currently the most in-demand instrument at the VLT and since its commissioning in 2014 it has served a broad scientific community covering many research fields in astrophysics. As a stable, relatively wide-field, two-dimensional, spectrophotometric facility in the optical, assisted by state-of-the-art adaptive optics, MUSE has revolutionised our perspective on the use of integral-field spectroscopy. This has been accompanied by a steep learning curve in the community on how to best reduce, analyse and exploit its unique datasets. This dedicated workshop was a unique opportunity to review the scientific achievements that MUSE has allowed over the last decade, to better understand and reflect on the synergies between MUSE and other facilities and to discuss the associated present and future challenges it entails. This workshop witnessed the gathering of a strong, diverse and interconnected community that could report on their experience and results and discuss potential avenues for the future, further emphasising the benefit of collaborative developments and shared knowledge.

Motivations

With its large field of view, broad wavelength coverage, state-of-the-art adaptive optics, and spectrophotometric capabilities, the Multi Unit Spectroscopic Explorer (MUSE) mounted on Unit Telescope 4 of the Very Large Telescope (VLT) quickly became a reference instrument addressing a rich and wide range of scientific questions. Combined with the powerful adaptive optics facility, MUSE has profoundly changed the way observers think and prepare their observing programmes. It has opened up new avenues into a variety of scientific topics covering, for example, galaxy formation and evolution, the nature of the circumgalactic medium, early stellar evolution, and stellar populations (see Figures 1 and 2). This 'MUSE at 10 years' workshop was organised to provide a timely opportunity to discuss past achievements, to probe synergies between integral-field spectroscopy and other existing or upcoming facilities, and most importantly to address the current and expected challenges and to nurture potential ideas for the future.

A particular focus of this four-day ESO workshop was on notoriously difficult aspects such as background subtraction, extraction of spectra in crowded fields, the low-surface-brightness regime, line spread function and point spread function measurement and homogenisation, astrometry and mosaicking. Speakers were specifically requested to highlight and address in their presentations existing and future synergies with other major facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA) and JWST — and soon ESO's Extremely Large Telescope — as well as to discuss the current challenges and prospects for science supported by integral-field spectroscopy, building on their MUSE experience.

The workshop

The programme[1], designed by the scientific organising committee (SOC), was split into half-day sessions that covered a broad set of topics, including the high-*z* Universe, the circumgalactic medium, gravitational lensing, galaxy evolution, planetary systems, the physics of galactic nebulae, globular clusters, and stellar populations, as well as the baryon cycle (for example, star formation, stellar-driven feedback) and AGN. Several upcoming and prospective projects were emphasised, including BlueMUSE and the Multi-conjugate-adaptive-optics-Assisted Visible Imager and Spectrograph (MAVIS) for the VLT and the Wide-Field Spectroscopic Telescope. Dedicated sessions were organised around data and tools, illustrating the MUSE data reduction and

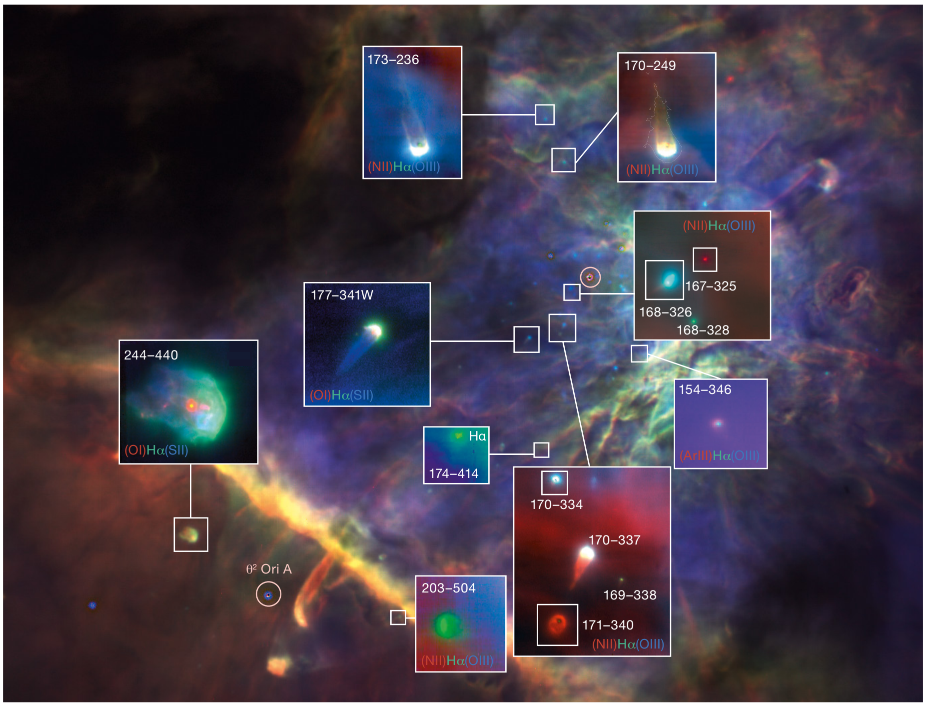

Figure 1. Insets: Reconstructed RGB images of continuum-subtracted, single-line integrated flux images of the sample of proplyds in a star formation region acquired with MUSE (Aru et al., 2024; Haworth et al., 2023). In each inset, various emission lines are combined to highlight the morphology of the proplyd. Background: Colour-composite using fluxes of three emission lines, with blue: Hβ, green: (N II) 6584, and red: (S II) 6731 (Weilbacher et al., 2015).

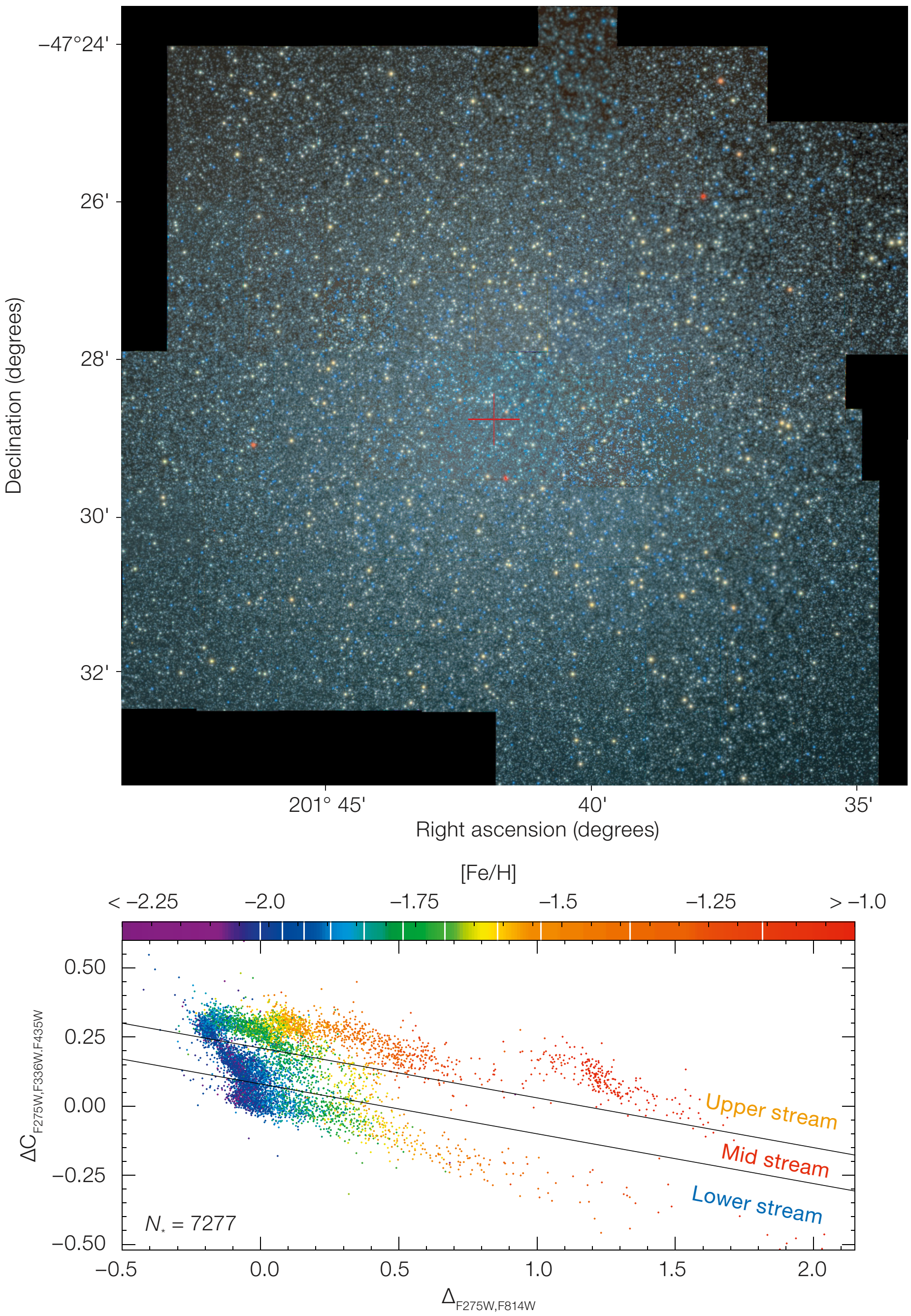

Figure 2. Top panel: Image of ω Cen. A three-colour RGB image of ω Cen created from MUSE WFM data using synthetic SDSS *i*, *r*, and *g* filters (Nitschai et al., 2023). The image displays the coverage of all WFM data (both GTO and GO). The red cross indicates the centre of the cluster. Bottom panel: Chromosome/pseudo-colour diagram for a sample of 7277 RGB stars in ω Cen, each star coloured by its metallicity. RGB stars are separated into three distinct streams using diagonal black lines and colour-coded labels. The edges of the [Fe/H] bins are indicated by white lines on the colour bar. Spreads in the $\Delta_{F275W,F814W}$ and $\Delta C_{F275W,F336W,F435W}$ within metallicity bins are primarily due to light element abundance variations (see, for example, Clontz et al., 2024).

analysis and how it connects to the ESO ecosystem. In a special 90-minute session, Peter Weilbacher introduced the ins and outs of MUSE data reduction, and Amelia Fraser-McKelvie led a discussion on an organised ‘Data Challenge’ (see below).

The conference gathered more than 140 scientists and engineers, with 110 local in-person attendees (Figure 3). The SOC managed to achieve a gender balance among the invited reviewing speakers, with just over a quarter of junior scientists. A blind (anonymised) selection of talks led to a majority (60%) of junior speakers, with a 30:70% ratio of female to male presenters (representative of the application pool).

The success story

One of the many highlights of this conference was the keynote speech by the PI of the MUSE instrument, Roland Bacon, reporting on the “Anatomy of a Success” and the lessons learned from both the design and construction phases and the decade of operational life of the instrument. The productivity and popularity of the MUSE spectrograph were clearly emphasised via various metrics, with a lower limit for the pressure between five and 10 depending on the allocation period. Some of the reasons for this success were analysed in the context of, for example, its broad scientific capabilities (see also Roth, 2024), performance and discovery power. As mentioned by Roland Bacon in his talk, MUSE and the ground-layer adaptive optics (GLAO) opened a window for very long integrations on the sky with excellent final image quality for an optical ground-based facility. One key aspect that allowed the realisation of such opportunities is associated with the vision attached to instrumental and software development, promoting new approaches to the design, construction and operation of a spectrograph. MUSE is the result of the efforts of a team of hard-working and creative people who had a science-driven vision for an ESO VLT instrument.

It is worth noting here that MUSE’s capability to blindly target a field, as applied, for example, to the MUSE Deep Fields (the talks by Bacon, Fumagalli, Wisotzki, Ciocan), was a game-changer but did not initially receive strong support from early reviewers.

Today, the most requested MUSE mode is the Wide-Field NO-AO mode, which

Figure 3. Conference picture of the participants in front of the ESO Supernova Planetarium & Visitor Centre, Garching.

has also been the most operated one at the telescope except for period P114. The relative under-use of the AO mode triggered discussions throughout the week, with the idea that the superb performance of MUSE with the GLAO and its ease of use may need to be further promoted.

This workshop also highlighted how the collaboration strategy from the MUSE GTO team (such as the organisation of Busy Weeks) has proven successful and is a great example for future instrument consortia.

A fair fraction of the 66 astrophysics talks demonstrated the powerful synergies between MUSE and other observational facilities such as ALMA, the Hubble Space Telescope, JWST and Chandra. This concerns, for example, deep and cluster surveys that have been systematically covered by multi-wavelength campaigns, allowing the probing of a large set of galaxies and structures or targeted observations where MUSE serves as a spectroscopic probe via multiple line and continuum tracers. We also witnessed a few more technical or method-oriented talks addressing, for example, the derivation of the point spread function produced during AO observations, and the use of machine learning algorithms to classify sources or push the extraction of information from MUSE datacubes. It would be impossible to cover all of the fine scientific results presented at the conference here. Still, we encourage readers to explore the presentations that will be made available via Zenodo.

The MUSE Data Challenge

While a remarkably solid reduction pipeline has been developed and maintained by the MUSE Consortium and ESO to address the complex (multi-CCD) MUSE dataset, issues remain that impact observing campaigns to various degrees. Some of these are common challenges faced by most/all integral-field spectrographs and have been addressed in various ways by different teams. Chief among these, for MUSE at least, are sky subtraction and flat-fielding. These problems will only become more prominent as the community continues to push MUSE to its limits over the next decade, specifically via its allocated Large Programmes: for example, the extraordinarily faint surface brightness limit imposed by the Generalising Edge-on galaxies and their Chemical bimodalities, Kinematics and Outflows out to Solar environments (GECKOS) programme, or the large contiguous sky regions that need to be covered with exceptional flux calibration that begins with sky subtraction by, for example, the Physics at High Angular resolution in Nearby GalaxieS (PHANGS) survey and MUSE and ALMA Unveiling the Virgo Environment (MAUVE). The SOC and the local organising committee (LOC) of the MUSE 2024 conference launched a 'MUSE Data Challenge', focusing on those two most pressing issues that will be key to further expand on the innovative science MUSE has so far delivered. Those issues apply to most modern integral-field spectrograph instruments and future facilities, so solving these problems is timely and relevant to the community over the coming decades.

The organising team, led by Amelia Fraser-McKelvie, provided the data challenge entrants with a set of raw object and calibration frames for two targets. Participants were encouraged to use any tools and techniques at their disposal (along with freedom of access to the entire ESO archive) to respond to two challenges: 1) to remove flat-fielding signatures from resultant reduced data cubes, and 2) to illustrate their best sky subtraction strategies. Despite the very tight schedule and the effort required, three scientists belonging to different teams responded to this call (Tania Urrutia, Jesse van de Sande and Johan Richard), and the results of their work were collated by the SOC/LOC and presented to the whole audience during the Data Challenge session. Each entrant provided creative and effective solutions to the set challenges, a summary of which can be found in the slides for this session (to be available on Zenodo). A discussion of the benefits and drawbacks of each approach, comparing various techniques in an 'apples to apples' manner with a standardised set of data followed. This further triggered the sharing of ideas to better address those and similar challenges, and further led to action items within the community and at ESO.

Looking forward, together with the community

The ESO MUSE 2024 conference provided a glimpse of the strong scientific community behind this amazing facility. It was pervaded by the unique feeling of a strong identity associated with the MUSE instrument and science, ensuring a large audience throughout the week despite the wide range of scientific themes that were covered (from planets to cosmology). The conference also highlighted the spirit of collaboration around MUSE data and science (exemplified, for example, during the Data Challenge session), with a desire to exploit this potential via the development of ideas and tools, to ultimately push the instrument’s limits even further. The ESO community and ESO itself should nurture these aspects to extend the synergetic potential of multi-wavelength and multi-facility science and to fully prepare for the arrival of the next generation facilities.

Acknowledgements

We sincerely thank all the members of the SOC and LOC and the ESO IT and logistics staff for their hard work and support. We would also like to thank Michael Hilker and the Garching Office for Science for their unconditional support. Particular thanks go to Denisa Tako for her patient and positive contribution to all aspects of the organisation.

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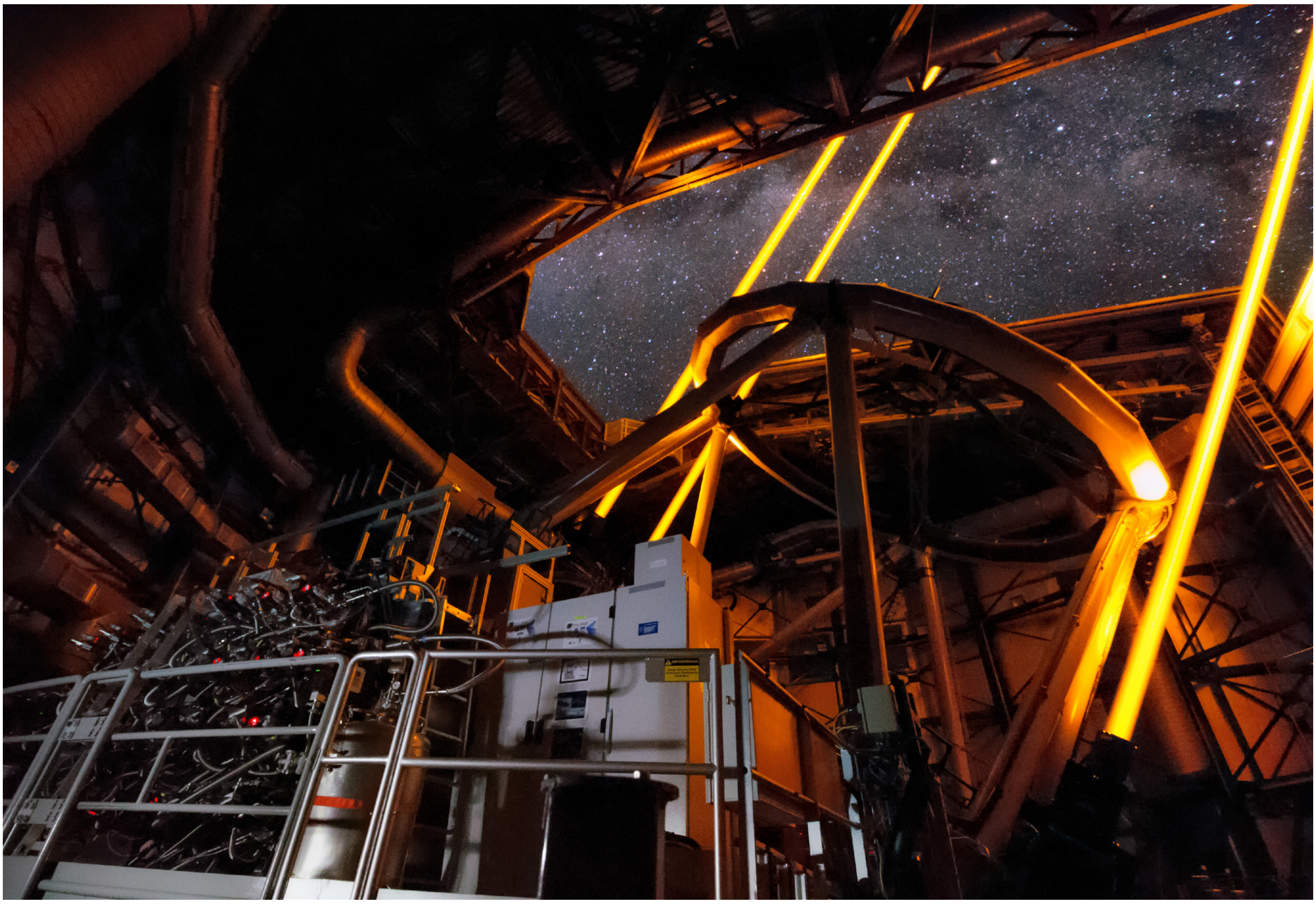
Haworth, T. J. et al. 2023, MNRAS, 525, 4129
Nitschai, M. S. et al. 2023, ApJ, 958, 8
Roth, M. 2024, RNAAS, 8, 54
Weilbacher, P. M. et al. 2015, A&A, 582, A114

Links

[1] Workshop programme: https://www.eso.org/sci/meetings/2024/muse24.html

Roland Bacon/ESO



Inside the UT4 of the Very Large Telescope, part of the Adaptive Optics Facility (AOF), the four Laser Guide Stars Facility, points to the skies during the first observations using the MUSE instrument. The sharpness and dynamic range of images using the AOF-equipped MUSE instrument will dramatically improve future observations.

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Fellows at ESO

Marta De Simone

"[…] I grew up in a cruel land where snow mixes with honey
And good people wear crowns of thorns on their heads
Since childhood, I have learned the difference between blood and wine,
that a life can be broken for a piece of meat or bread
And I can't get used to all this happiness […]"
Brunori Sas

These words resonate with me deeply, as I grew up in a small town in Calabria (southern Italy), where the snow shines in winter, and the sky is so dark you can see the Milky Way in all its colours. I was raised in a modest family that valued culture and study, encouraging me to explore my curiosity and seek knowledge.

One evening, when I was about 12, I noticed a bright point of light in the sky, just above a mountain on the horizon. It was not a streetlight or a plane and I couldn't stop thinking about it. I was curious and seeking an explanation and my mother, who did not know what it was, encouraged me to investigate. Through my research, I slowly realised I was looking at Venus, and the discovery blew me away. Beyond that, I was always mesmerised by the night sky. On drives home from the mountains, I'd press my face against the car window, capturing every second of that amazing starry sky. Since then, I started learning the constellations and spending every chance I could looking up.

At the same time, I was always drawn to music. I started playing the flute, following in my sister's footsteps, and dreamed of attending the conservatory. But my mother encouraged me to think carefully, reminding me of the challenges my sister had faced. On the other hand, my sister tried to push me to carve my own path. In hindsight, I thank them both, because I later realised that my true passion in music was not playing an instrument but singing. That became clear when, almost by chance, I joined the church choir in my home town. At first, I was extremely shy and promised myself I would only ever sing within my room's walls. But that promise did not last long. I never left the choir, and no matter where life took me, I always looked for one to join. Singing became my escape valve, my way to release emotions.

As high school came to an end, I had to decide what came next. In southern Italy, university was the natural step after high school, as the job market offered few alternatives. But I still had no clear direction. I considered scientific criminology (to solve homicides and mysteries), medicine (inspired by my father, who was a nurse), and, finally, something related to stars (as astrophysics). But the idea of pursuing physics felt intimidating. I had struggled with it in high school, changing teachers every year, none of whom were particularly inspiring. However, in my final year, a new physics teacher arrived showing us physics in a new light and speaking of vast research frontiers. When I shared my interest in astrophysics, he and my maths teacher encouraged me to go for it. Their support gave me the courage to try. I moved to Florence, 800 km from home, to pursue a bachelor's in physics. The journey wasn't easy, but worth it. Over time, even my male classmates, skeptical and envious, came to recognise my determination and the difficult path I had chosen, one they hesitated to follow.

At university, I didn't even fully understand what a doctorate was, nor the path to an academic career. That changed when I had the incredible opportunity, after meeting with Leonardo Testi at the University of Florence, to carry out my bachelor thesis project at ESO. It was my first approach to the world of research, and the opportunity to see what an international institute running the most powerful ground-based telescope looked like. I fell in love with the place, the inspiring people working there, and the atmosphere of curiosity. This sparked a desire to return for my master's thesis. Soon after, I was offered a PhD position on astrochemistry, the topic of my bachelor thesis, to work with one of the leading experts in the field, Cecilia Ceccarelli. I was overjoyed and truly grateful for this opportunity. During my PhD, I studied how molecules form in space and how the building blocks of life might have reached Earth, observing the gas in young stellar nurseries. It was a dynamic and enriching journey filled with people from diverse backgrounds, wide range of topics with unexpected and fascinating ramifications and changes of directions. It allowed me to grow into an independent scientist, ready to compete for a prestigious ESO fellowship.

Joining ESO as a fellow was a dream come true. It brought me back to the place that had captivated me and made me fall in love with research. As a fellow, I spend most of my time studying the origins of chemical diversity in regions where stars and planets form. I could also support the observatory, contributing up to 25% of my time with functional work at the ALMA Regional Center, gaining invaluable insights into how an international major observatory runs. One of the most unforgettable moments was the visit the ALMA site in Chile, where I conducted observing runs and witnessed the magnificence of the 60 antennas on the Chajnantor plateau at 5000 metres. I once again felt like that child with my face pressed against the car window, soaking in every moment of that dark, but colourful starry sky. At ESO I also met a few students who shared my passion for singing. I then pushed them to create a small choir to have a place where people could sing, relax, and unwind after long days of work. Two years later, the choir is still going, and it is very well-received and full of the enthusiasm of the participants.

Today, I feel privileged to be an astronomer at ESO, and I hope to always retain the astonishment and curiosity I felt at the beginning of my research journey. Now, I aspire to be like those who inspired me at ESO, and to guide and encourage the future generation of astronomers.

Julien Drevon

My name is Julien Drevon, I am 27 and I grew up in a loving home in the city of Cannes, France, right in the heart of the French Riviera. The sun, the sea, the mountains, and the clear skies provided by the nearby Alps created the ideal conditions for nurturing a passion for astronomy and the many celestial objects of the night (and day) sky.

Like most people working in the field, my passion began at a very young age. If you asked my mother, she would tell you that I hadn't even mastered the French language yet, but I was already trying to express my fascination with the Moon every time I saw it.

After a standard academic path and upon turning 17, I followed the usual trajectory of French students pursuing higher education. I completed a year of preparatory studies for the competitive entrance exams to the prestigious Grandes Écoles, which I passed. This experience taught me valuable study methods, but the pace and teaching style did not suit me. So, I decided to continue my second year directly in a physics bachelor's programme at the university. The unlimited access to knowledge, group work, and independent learning were exactly what I needed. From that point on, my academic journey followed a more traditional route.

I earned my bachelor's degree in physics with an astrophysics specialisation, followed by a master's degree and a PhD in astrophysics at Université Côte d'Azur in Nice. My area of expertise focuses on studying the molecular and dusty environments of evolved stars in the infrared using interferometric observations.

During the second year of my PhD, I had the pleasure of being selected for the ESO Studentship programme in Santiago. At ESO, I was mentored by experienced astronomers who shared their knowledge and passion, allowing me to conduct research and gain expertise that I would not have been able to acquire without their guidance.

After completing my PhD, I was fortunate to be selected by the ESO Fellowship committee to become an integral part of the team of astronomers and researchers based in Santiago. For over a year now, I have had the privilege of wearing two hats: I am both a researcher and a night astronomer.

As an ESO researcher, I strive to understand how and under what conditions dust forms around dying stars. Dust and the heavy elements produced by stars are the fundamental building blocks of life as we know it on Earth. By understanding how this dust forms, we are essentially trying to understand our own origins. To observe the objects and environments I study, I need telescopes over 100 meters in diameter. This is where interferometry comes into play: by combining multiple telescopes, we can achieve a resolution equivalent to that of a single 100-metre telescope. At Cerro Paranal, we do this using either the 8-metre telescopes or the smaller 1.8-metre telescopes.

Large diameters are useful when observing faint objects that require collecting large amounts of light to detect their signal. However, the objects I study are bright enough to be observed with the 1.8-metre telescopes. An additional advantage of these smaller telescopes is their mobility; they can be repositioned at different locations on the platform, allowing us to scan an object from multiple angles and achieve resolutions ranging from a few metres to the equivalent of a 200-metre telescope — five times the resolution of ESO's Extremely Large Telescope (ELT) currently under construction at Cerro Armazones.

Interferometry does not directly produce images of our environment. Instead, we observe the intensity and phase of the interference patterns between the light collected by different telescopes. My expertise involves gathering, calibrating, and analysing these data. If enough observations are available, I can reconstruct an image of the environment surrounding an evolved star.

In July 2024 I won, on behalf of ESO, the image reconstruction contest at the SPIE 2024 workshop. This competition, along with the scientific challenges presented by my data, continuously pushes me to refine my skills and improve my image reconstruction techniques. My long-term goal is to help the interferometry community reconstruct images more efficiently by making the process less tedious and more accessible so that more researchers can obtain high-quality images.

My second role at ESO, given my expertise, is to operate the VLTI instruments at Paranal for 80 nights a year. I conduct observations for astronomers worldwide whose proposals have been selected by an ESO committee. Once a proposal is approved and the target is observable, my role is to provide the best possible data from one of the most optimal observing sites on Earth.

I see this dual role as a significant advantage, especially as someone who completed their PhD just over a year ago. On the one hand, I have the opportunity to experience full research autonomy, collaborate internationally, and work on topics I am passionate about. On the other hand, I gain hands-on expertise in interferometric data observation, learn the inner workings of an observatory, and develop my skills as a night astronomer.

This is an opportunity unlike any other, and I feel incredibly fortunate and proud to share this experience, thanks to ESO.

Elizabeth Artur de la Villarmois

My love for the Universe started in my childhood, when watching documentaries about the origin of the Universe, the Solar System, and Earth's formation, filled with pretty images and captivating simulations. At some point my parents bought me a set of little stars that shine during the night, and I glued them on the ceiling of my room, so every night I fell asleep 'under the stars'.

I was born in San Pedro de Jujuy, a city located in the north of Argentina, and I spent most of my childhood in Salta, two cities very close to each other and at a similar latitude as ALMA (just on the other side of the Andes). Before finishing high school, I really wanted to study astrophysics. This wasn't something temporary that faded with time and, as university application time approached, I had to get serious and started considering my possibilities. Coming from non-scientific family, I didn't know what were the steps to follow to become a scientist or what kind of future to expect. I just knew I wanted to be an astrophysicist. I still remember that my parents were a little worried about my future, but they still supported me and I will always be grateful for that.

My adventure began when I moved to the city of Córdoba, 900 km from my hometown, to study astronomy. I think Argentina is one of the few countries that has an astronomy course that lasts five years, unlike other countries where one studies physics and then specialises in astronomy. I really enjoyed my student life and, with some ups and downs, I managed to finish my course, my thesis being about infrared jets in forming stars.

After graduating, the next step was to apply for a PhD position with funds from CONICET, the national scientific and technical research council. But, after applying for two years in a row, I didn't win the grant. That was a difficult moment and I had to sit down, reflect, and explore other paths. I began teaching maths and physics to first-year university students while applying for a master's programme in Rio de Janeiro, Brazil. I won that grant and, for the first time, I moved to a different country — and one with a different language.

During my two years in Brazil, I began working with submillimetre observations. My supervisor at that time put me in contact with an expert in the field, and I feel like that was a pivotal moment in my scientific career. At that time, ALMA was in its cycle-2, already making revolutionary

discoveries. A few months before finishing my master's, I saw a PhD position advertised in Copenhagen, Denmark, in my research area and fully focused on ALMA data. The professor offering the position was the author of several papers that guided me during my master's so, even though I had no idea at that moment about Denmark, I really wanted to work with him. Fortunately, he offered me the PhD position!

Living in Denmark was a huge change for me, in terms of culture, distance, people, weather, politics, food, and friends. I fell in love with the bicycle culture, which I still enjoy today. During my three years of PhD, I began submitting ALMA proposals, I wrote first-author papers, I became more skilled in submilletre/millimetre data analysis, and I felt passionate about astrochemistry. After my PhD, I applied for postdoctoral positions in many countries like Sweden, Germany, Chile, and the USA. I was awarded a three-year grant in Chile, as a FONDECYT postdoc at Pontificia Catholic University (PUC), in Santiago.

My plan was to start my postdoc in April 2020, but COVID-19 hit just before. I had started my visa process to come to Chile, but the Chilean embassy in Copenhagen stopped all the processes until August, when flights partially resumed. I managed to arrive to Chile in August 2020, in the middle of the lockdown. The first months were challenging, mainly because of paperwork and bureaucracy, but I was closer to my home country, so the culture shock was not a big deal.

Living in Santiago I fell in love with the mountains and with the man who later became my husband. During these three years, I learned more about ESO and ALMA by attending workshops and conferences in Vitacura. I remember the first time I walked outside the Vitacura campus, where there are many beautiful images of the Universe and the telescopes, and I thought "I would love to work in this place." So when my FONDECYT postdoc was near its end, I applied for an ESO fellowship to work with ALMA. Honestly, I thought my chances were low, given that Argentina is not an ESO Member State, so it was a lovely surprise when I was accepted at ESO.

I began my ESO fellowship in May 2023, and I feel I have learned a lot in this period of time, especially about the observational aspects of ALMA and how things happen behind the scenes. Visiting the antennas at 5050 metres for the first time was a dream come true, and I still enjoy it a lot every time I have a shift at the high site. But not everything is ALMA; in late 2023 I visited Paranal and the ELT, which was halfway through construction. That was breathtaking!

My current research focuses on understanding how stars and planets, like our own Solar System, form and evolve. Using ALMA observations, I study the chemical composition of these systems and their potential to harbour life in the future. Many unanswered questions remain, but the future looks bright, with upcoming new capabilities like the ALMA 2030 upgrade and the ELT's first light. Stay tuned!

ESO/G. Vecchia

Bathed in the sunset light of Chile's Atacama Desert, this image shows steady progress in the construction of ESO's Extremely Large Telescope (ELT).