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The ATOMIUM Large Programme Science Results

Pushing Further the Limits of Near-Infrared Interferometry with GRAVITY+

ESO@60: A stairway to the Universe Symposium

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Contents

Astronomical Science

Decin, L. et al. – ATOMIUM: ALMA Tracing the Origins of Molecules In dUst forming oxygen-rich M-type stars 3
Sarzi, M. et al. – The Fornax3D Survey — A Magnitude-Limited Study of Galaxies in the Fornax Cluster with MUSE 9

Telescopes and Instrumentation

GRAVITY+ Collaboration – The GRAVITY+ Project: Towards All-sky, Faint-Science, High-Contrast Near-Infrared Interferometry at the VLTI 17
Padovani, P. et al. – The ESO's Extremely Large Telescope Working Groups 23

Astronomical News

Guzmán Mesa, A. et al. – ESO's Role in Advancing the UN Sustainable Development Goals 33
Arnaboldi, M. et al. – Report on the EAS Symposium "ESO@60: A stairway to the Universe" 37
Hibon, P. et al. – Report on the Workshop "Joint Observatories Kavli Science Forum" 42
de Gregorio-Monsalvo, I. et al. – Work-Life Balance Round-Table Discussion at the Joint Observatories Kavli Science Forum 44
Alcalde Pampliega, B. et al. – Diversity, Equity, and Inclusion Round Table at the Joint Observatories Kavli Science Forum 46
Kokotanekova, R. et al. – Report on the ESO Workshop "Solar System Science with the ELTs" 48
Koumpia, E., Harrington, K. C. – Fellows at ESO 51
Janout, P. – Engineering Fellows at ESO 54
Lyubenova, M. – The Messenger to Become an Online-Only Publication 55

Front Cover: Messier 61 is one of the largest members of the Virgo Cluster of galaxies. The gas and dust of the intricate spiral arms are studded with billions of stars. This galaxy is a bustling hub of activity with a rapid rate of star formation, and both a massive nuclear star cluster and a supermassive black hole buried at its heart. The image was taken with the FORS2 instrument on the Very Large Telescope as part of ESO's Cosmic Gems Programme, which is an outreach initiative to produce images of interesting, intriguing or visually attractive objects using ESO telescopes, for the purposes of education and public outreach.

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ATOMIUM: ALMA Tracing the Origins of Molecules In dUst forming oxygen-rich M-type stars

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Karl Menten[11]
Tom Millar[13]
Iain McDonald[14]
Miguel Montargès[12]
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The goals of the Atacama Large Millimeter/submillimeter Array (ALMA) Large Programme ATOMIUM are to obtain a quantitative understanding of the chemical and physical processes that govern the phase transition from small gaseous molecules to dust grains in the inner wind of oxygen-rich evolved stars; and to study the interplay between dynamical and chemical phenomena in the outflow of 17 asymptotic giant branch (AGB) and red supergiant (RSG) stars which span a range in (circum) stellar and wind properties — such as mass-loss rate, pulsation behaviour, and spatial structure of the wind-dominated ambient medium. The observations were made with three configurations of the ALMA array that encompass a range in angular resolution of approximately 0.02–1 arcseconds. They consist of 27-GHz-wide homogeneous spectral-line and continuum surveys in the 214–270 GHz range in each source in the sample, and provide an unambiguous comparison among sources. Equipped with these tools, we then show how the stellar winds of all the ATOMIUM sources exhibit distinct non-spherical geometries that can be explained by binary interaction and — depending on the parameters of the binary system — can produce a wide variety of morphologies as illustrated by the example of the AGB star π^1 Gru. In parallel with ATOMIUM, contemporaneous observations of all but three of the 17 sources were made in the visible with the SPHERE/ZIMPOL instrument at ESO's Very Large Telescope (VLT). The VLT/SPHERE observations provided direct images of the dust at a spatial resolution comparable to that obtained with ALMA. Novel hydrodynamical simulations of binary systems were done so as to further the interpretation of the near simultaneous observations of the gas and dust. We also present a brief overview of the 24 molecules that were identified in the survey, followed by a discussion of how the molecules inform us about the inner wind and the (super)giant outflow, and of some future possible observations with ALMA, ESO instruments, and the JWST.

ATOMIUM motivation and survey strategy

Scientific goals

Over 200 molecules and 15 dust species have been detected in the interstellar medium, stellar winds, exoplanets, supernovae, active galactic nuclei, etc. One of the most fundamental questions in astrophysics deals with the phase transition from simple molecules to larger gas-phase clusters and eventually dust grains. The outflows of evolved stars are the best laboratories in which to answer this pivotal question, given their rich chemistry and relatively simple dynamical structure. With the Atacama Large Millimeter/submillimeter Array (ALMA) Large Programme ALMA Tracing the Origins of Molecules In dUst forming oxygen-rich M-type stars (ATOMIUM[1]) we aim to establish the dominant physical and chemical processes in the winds of oxygen-rich evolved stars over a range of stellar masses, pulsation behaviours, mass-loss rates, and evolutionary phases. The goals are to unravel the phase transition from gas-phase to dust species, pinpoint the chemical pathways, map the morphological structure, and study the interplay between dynamical and chemical phenomena (Gottlieb et al., 2022). To achieve these goals, an ALMA Large Programme was submitted and accepted in Cycle 6 for a total observing time of 113.2 hours. This is still the only accepted Large Programme in the field of Stellar Evolution and the Sun.

ATOMIUM sample and observing strategy

The ATOMIUM sample consists of 17 oxygen-rich evolved stars, which span a range in (circum)stellar and wind properties, such as: mass-loss rate, pulsation behaviour, and asymptotic giant branch (AGB) versus red supergiant (RSG) stars. The sample consists of 14 AGB stars that are relatively close to Earth and three RSG stars. The selection criteria did not take into account prior evidence for possible binary companions.

A primary requirement for the ATOMIUM project was for homogeneous observations across the sample that would allow unambiguous comparison among sources. The most efficient way to achieve the science goals with ALMA was to target specific spectral frequency regions in Band 6, where we know which molecules to monitor to answer the questions about the dynamical behaviour and chemical processes in the winds of evolved stars.

To spatially resolve the dust condensation region ($r \leq 10–30\ R_\star$, where $R_\star$ is the stellar radius), an angular resolution (AR) of 0.025–0.050 arcseconds is needed for our targets, which all have large optical stellar angular diameters of between 0.004 and 0.020 arcseconds. The highest spatial resolution for each target was about 0.02 arcseconds. To attain the full line strength of the molecular lines, we complemented these observations with data from a medium-resolution (AR ~ 0.20 arcseconds) configuration and a low-resolution (AR ~ 1 arcsecond) configuration. In aggregate we resolve the emission on scales from the stellar radius to thousands of stellar radii.

ATOMIUM data reduction and data products

The ATOMIUM enhanced data products are being prepared for the ALMA archive. The starting point is the standard ALMA pipeline (or occasionally manual Quality Assurance 2) products. We combined the data for each star across the observed frequency range, as described by Gottlieb et al. (2022), and provide a description document and scripts for each star. These cover self-calibration (using stellar continuum), imaging and extraction of spectra. Three fully calibrated measurement sets (MS) are provided for each star, for each of the three array configurations: a continuum MS (120 channels per 1.875 GHz), a line MS (1920 channels per 1.875 GHz with about 1.2 km s^{-1} resolution) and a continuum-subtracted line MS. We also combined the data for each star for all configurations, giving one MS for the calibrated continuum visibility data (after flagging line channels) and another for the continuum-subtracted line data. The MS are a suitable starting point for re-imaging, for example to select a particular line and use different averaging or weighting to improve the sensitivity or to change the angular or spectral resolution.

Ready-made spectral cube images are available for each spectral window and array configuration (low, medium and high spatial resolution). They provide an angular resolution of approximately 0.8, 0.2 and 0.02 arcseconds, and sensitivities of a few mJy per channel. A fourth set of cubes was made from the combined data. All cubes were made using consistent parameters, but users can also take the calibrated visibility data to make images at customised resolutions to favour lines or features of interest. We made continuum-only images for each of the three configurations and the combined data, which is dominated by stellar emission (resolved at the higher resolutions) and sometimes also reveals hot dust. For the exact frequencies covered, angular resolutions, sensitivities and other details, see the appendices of Gottlieb et al. (2022). The final set of archived products are spectra extracted from each cube, for a range of extraction aperture radii (depending on configuration) from 0.02 to 5.4 arcseconds.

Hydrodynamical behaviour of stellar winds

Companions shaping the winds of AGB and RSG stars

The new revolution in observational techniques accommodates high-spatial-resolution (reconstructed) images and provides direct evidence that the circumstellar envelopes created by the stellar winds harbour small- and large-scale inhomogeneities. Flow instabilities induced by convection result in the formation of granulation cells on the surfaces of the giant stars, and of small-scale density structures in the stellar wind, with sizes of about 1–50 au. A remarkable new thesis delivered by the ALMA telescopes is that planetary or stellar companions impact the wind morphology of almost all AGB and RSG stars with a mass-loss rate

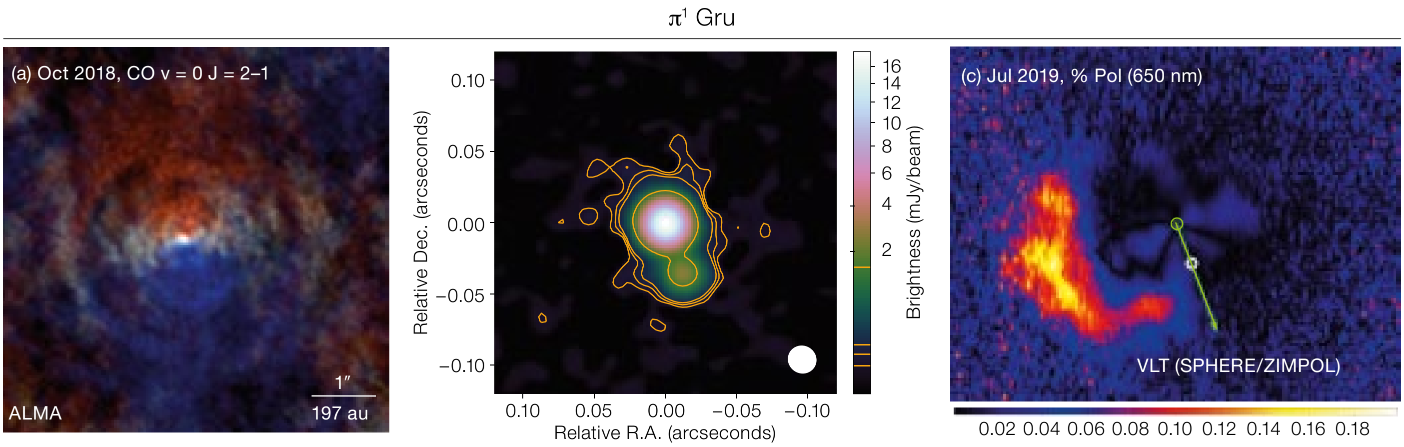

Figure 1. ALMA and VLT SPHERE/ZIMPOL observations towards π^1 Gru. (a) ALMA ATOMIUM CO v = 0 J = 2–1 emission map of the wind structure of π^1 Gru; angular resolution of ~0.3 arcseconds. (b) ALMA 1.2-mm continuum emission towards π^1 Gru at epoch July 2019; angular resolution of 0.019 arcseconds. Contours (in orange) are plotted at 3, 6, 10 and 100 times the continuum noise value. The secondary peak (white circle) south-west of the central star is likely due to a close companion. (c) SPHERE/ZIMPOL percentage polarisation at 644.9 nm towards π^1 Gru at epoch July 2019; angular resolution of 0.024 arcseconds.

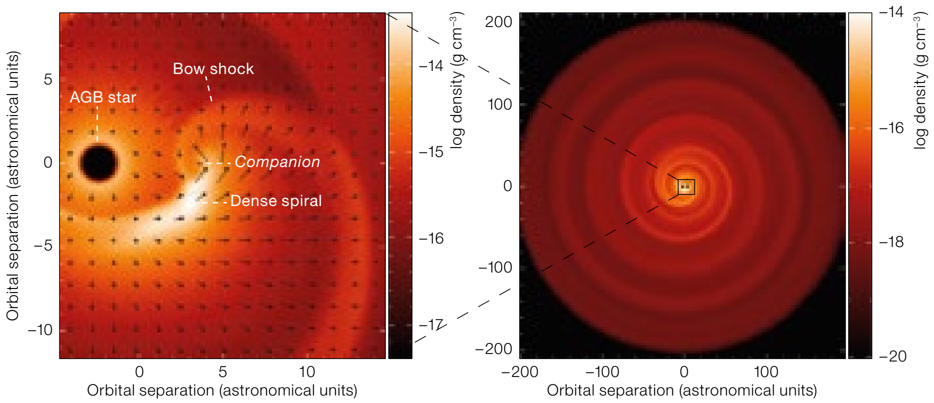

Figure 2. Density distribution in a slice through the orbital plane for the binary configuration described in the text, with the centre of mass located at the (0,0) position. The left panel shows the inner density structures formed around the primary and the companion; the right panel displays the global orbital plane morphology (Malfait et al., 2021).

$\dot{M} \geq 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$. In a fraction of stars, the companion induces a change in the wind's expansion velocity and mass-loss rate.

In particular, we have shown that the winds of all sources observed within the ATOMIUM programme exhibit distinct non-spherical geometries with extents greater than about 100 au, and morphologies which are similar to those of planetary nebulae (Decin et al., 2020). These morphological characteristics can be explained by binary interaction. Depending on the parameters of the binary system, a wide variety of morphologies can arise, including spiral structures, a circumbinary disc, an accretion disc around the companion, a bipolar outflow, an equatorial density enhancement. An example of such a binary-induced morphology is shown in the left panel of Figure 1, which displays the ATOMIUM CO $v = 0$ $J = 2$-1 emission map for the AGB star π^1 Gru (Decin et al., 2020). Emission that is redshifted with respect to the local standard of rest velocity is shown in red, blueshifted emission is in blue, and the gas at the rest velocity is in white. The scale bar has an angular extent of 1 arcsecond. Prior to the ATOMIUM data, it was known that π^1 Gru has a companion residing at about 440 au. However, that companion is too far away to create the structures revealed by the observations with ALMA. Remarkably, the ALMA continuum data (middle panel of Figure 1) show two maxima separated by about 6 au. An investigation of the ALMA continuum data — and the maps of the CO, SiO, and HCN emission — reveals that the second maximum could be a companion of mass $\lesssim 1.1\,M_\odot$ that creates an inclined, radially outflowing equatorial density enhancement and a spiral structure (Homan et al., 2020).

VLT SPHERE/ZIMPOL observations

The ALMA ATOMIUM data only provide minimal inference of the geometry of the dust distribution around the AGB stars. For that reason we have acquired contemporaneous observations of the ATOMIUM sources using the SPHERE/ZIMPOL instrument at ESO's Very Large Telescope (VLT). The ZIMPOL instrument provides polarimetric images in the visible at an angular resolution that is comparable to the highest spatial resolution in the ALMA data (right panel of Figure 1). The observed polarized light comes from the scattering by the dust grains and originates primarily from regions near the plane of the sky going through the centre of the target. Green and white circles mark the inferred locations of π^1 Gru and the close companion. The companion is not directly seen in the ZIMPOL images, but is inferred to lie at the head of the spiral structure created by the gravitational interaction between the AGB star (and its wind) and the companion (Montargès et al., 2022).

Hydrodynamical simulations

To further the interpretation of the ALMA and SPHERE observations, we have performed novel hydrodynamical simulations for binary systems in which the primary is a mass-losing AGB star (El Mellah et al., 2020; Maes et al., 2021; Malfait et al., 2021). Figure 2 shows the density distribution for a simulation in which the primary star is an AGB star of mass 1.5 $M_\odot$ that launches a stellar wind with initial velocity of 10 km s^{-1} and mass-loss rate of $1 \times 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$. A companion star of mass 1 $M_\odot$ orbits the AGB star in a circular orbit with orbital separation of 6 au. The wind–companion interaction creates a dense spiral flow behind the companion and a second spiral emerging from a bow shock in front of the moving companion (left panel of Figure 2). This stable bow shock shapes the global morphology into an approximate Archimedes spiral structure (right panel of Figure 2).

Chemical processes in stellar winds

Twenty-four molecules were identified in the ATOMIUM sample by means of their rotational spectra (CO, SiO, HCN, SO, SO_2, CS, SiS, H_2S, OH, H_2O, TiO, TiO_2, AlO, AlOH, PO, SiC, SiC_2, SiN, CN, HCCCN, AlCl, AlF, NaCl, KCl). The first three molecules were observed in all the stars in our sample, but some of the others were observed primarily in the denser regions of the stellar wind in only some of the stars.

Shown in Figure 3 is a small portion of the spectrum observed in the oxygen-rich Mira variable R Hya, accompanied by high-resolution maps of the integrated intensity. The spectrum contains several species believed to be precursors of the dust, including TiO in the ground and first excited vibrational level (1451 K above ground), three transitions of vibrationally excited SiO (between 1790 and 5266 K above ground), and (see Figure 4) vibrationally excited H_2O and highly excited transitions of OH (5480 K above ground). Measurements such as these provide a direct means to examine the properties of the inner wind, and serve as benchmarks for the chemical kinetic calculations.

Because our observations allow us to examine a wide variety of chemical species found throughout the stellar

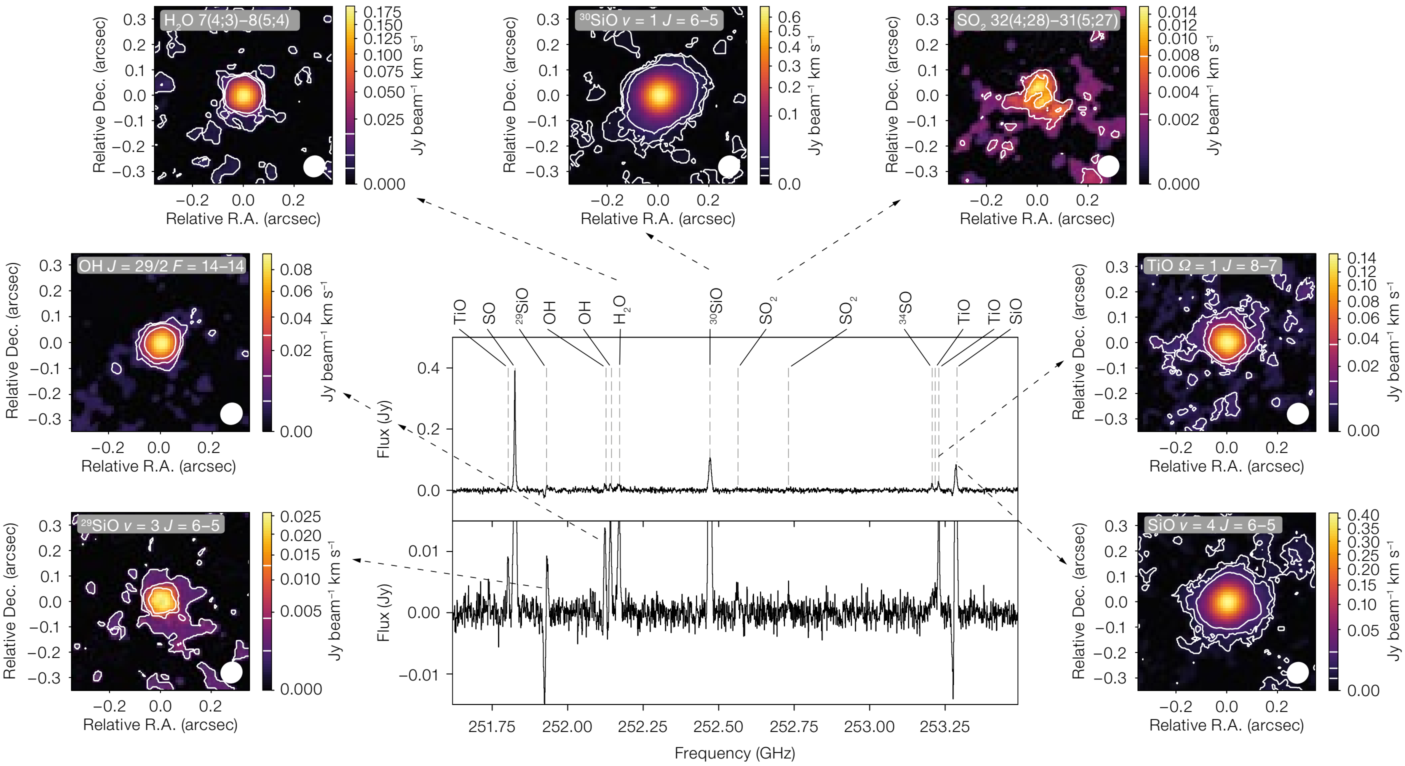

Figure 3. R Hya. Upper panel: Spectrum extracted from the medium-spatial-resolution configuration for an aperture of 0.2 arcseconds. Lower panel: Spectrum extracted from the high-spatial-resolution configuration for an aperture of 0.02 arcseconds. Images show the integrated intensity maps for some molecular lines computed from the combined dataset. White contours are at 3,10 and 30 times the noise in the integrated intensity maps. The ellipse in the bottom right corner of each image represents the beam of the combined dataset.

wind, we are able to refine the chemical kinetics codes used to predict the molecular abundances. For example, we established that the wind density plays a key role in wind chemistry, on the basis of an analysis of our recent observations of AlCl and AlF towards W Aql in close collaboration with physical chemists (Danilovich et al., 2021).

Overall, the ATOMIUM observations allow us to investigate several major astrochemical topics. These include: (i) molecules in the inner few stellar radii that are expected to be intimately involved in the formation of the initial dust grains; (ii) the interpretation of the spectra of 10 transitions in H_2O (Baudry et al., 2022, and see Figure 4) and vibrationally excited SiO which are both sensitive tracers of clumps, shocks, and complex gas motion; (iii) detailed analyses of the spectra and maps of CO and SiO (in maser and non-maser emission) that reveal the morphology and the wind dynamics in the inner wind and throughout the outflow in all the stars — supplemented with the maps and spectra of other molecules, such as HCN (Homan et al., 2020) and SO_2 (see, for example, Figure 4 of Gottlieb et al., 2022); (iv) constraining the reaction rates used in chemical kinetic codes that aim to reproduce the molecular abundances derived from the ATOMIUM observations in each stellar type, and the quantity of the dust inferred from the VLT/SPHERE-ZIMPOL observations of Montargès et al. (2022); and (v) looking for the possible influence of companions on the chemistry in the inner wind (Van de Sande & Millar, 2022).

Another important area involving the gas-dust interactions which has begun to be addressed by recent chemical kinetic codes (Van de Sande, Walsh & Danilovich, 2020), concerns the deposition of the more abundant molecules on the grains in the AGB outflows. However much remains to be done by observers, working in close collaboration with chemists. The crucial observational quantities needed are reliable estimates of the fraction by which the abundances of key molecules (for example, SiO, SiS, H_2O, HCN, CS, and SO_2) are depleted in the outflow versus the distance from the star.

Other topics addressed by ATOMIUM

Building on the core goals of the ALMA ATOMIUM Large Programme, the ATOMIUM team[2] has grown during the past few years and currently includes 48 researchers with complementary expertise. ATOMIUM team members have addressed or are currently addressing: (i) the small- and large-scale morphologies of AGB and RSG stellar winds; (ii) the cause of inhomogeneous mass-loss events in RSGs; (iii) the distribution of molecules in the winds of AGB and RSG stars; (iv) quantum-chemical calculations of the cluster geometries and reaction rates of dust-forming gaseous precursors; (v) the molecular assignment of still unidentified spectral features; (vi) maser emission, in particular SiO masers to

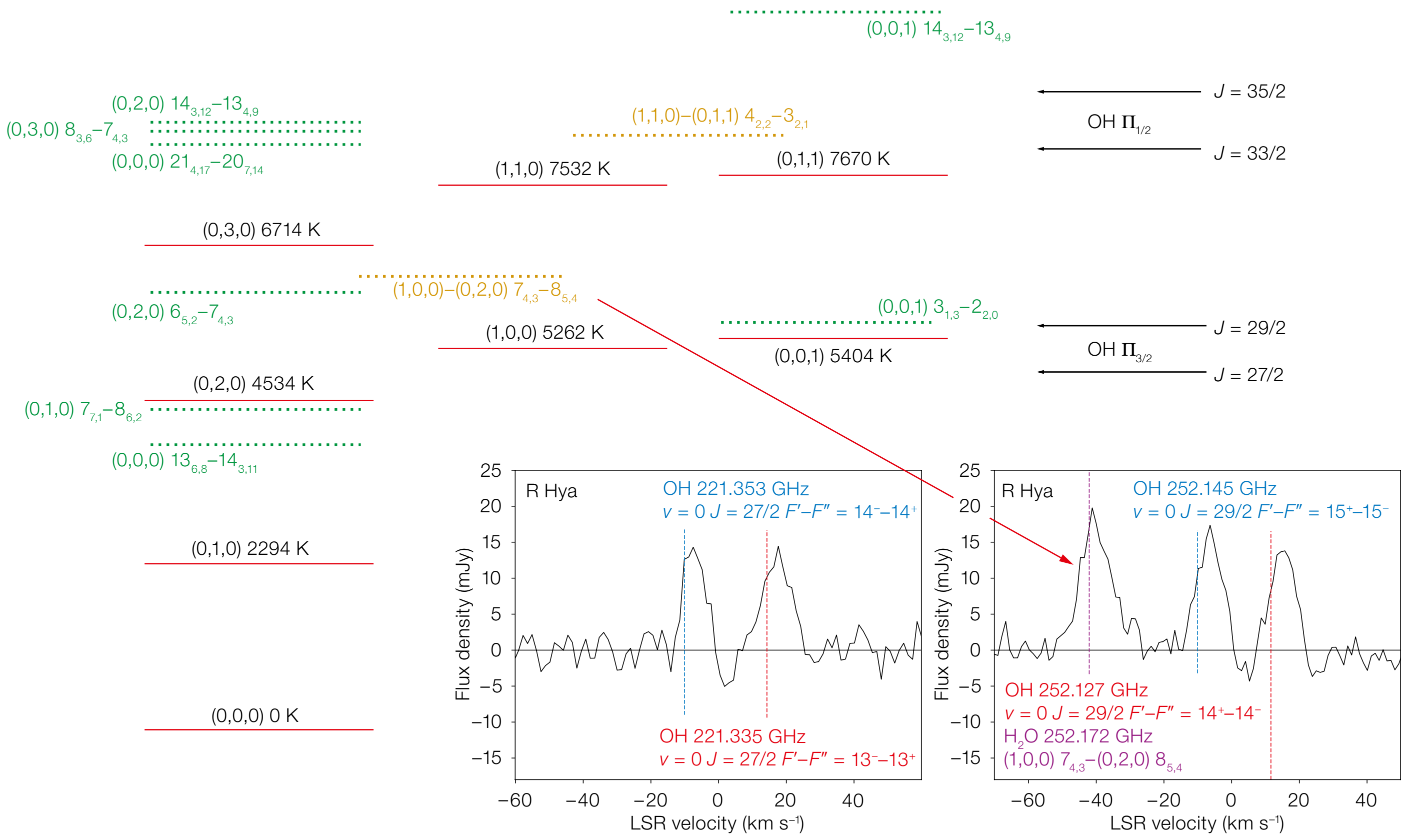

Figure 4. The lowest eight vibrational states of H_2O are displayed as horizontal red lines with their quantum numbers (v_1, v_2, v_3) and associated energy in kelvins. The horizontal dotted green and orange lines are the ten rotational transitions observed in various vibrational states of the ATOMIUM survey. The four horizontal black arrows to the right show the energy levels of the OH Λ-doublet transitions in the four rotational states observed in our survey. The two lower right panels present the J = 27/2 and 29/2 Λ-doublet spectra observed in R Hya, simultaneously with one rovibrational transition of H_2O next to the J = 29/2 OH spectrum (rightmost panel). The observed frequency is converted to velocity in the Local Standard of Rest frame by using the rest frequencies shown above and below the spectra corrected for the systemic star velocity (Baudry et al., 2022).

constrain excitation models as well as the kinematics close to the star, whilst conditions out to the wind acceleration zone are probed by water masers; (vii) the construction of chemical networks of relevance for AGB and RSG winds, and the study of their chemical predictions including that of dust nucleation; (viii) morphological studies of binary systems based on state-of-the-art hydrodynamical (HD) numerical codes; (ix) coupling of the HD codes to fast chemical network emulators and radiative transfer calculations; and (x) laboratory studies aimed at understanding dust nucleation/sublimation, and molecular collisions between water and H_2 or He, etc.

Next (observational) steps

The ATOMIUM Large Programme was designed to study oxygen-rich evolved stars via spatially resolved maps of molecular line and dust emission. From our first paper (Decin et al., 2020) it is already clear that binarity is a key parameter for understanding the chemical and morphological complexities of an evolved star's winds, although that parameter was not included in the original sample selection criteria. Aiming to understand the impact of (hidden) planetary and stellar companions, the ATOMIUM source sample should be extended to include carbon-rich evolved stars, oxygen-rich evolved stars for which we know the initial mass, and a larger variety of red supergiants. In addition, there is the need for complementary ALMA data targeted, on one hand at the same frequency bands to derive the time variability of morphological and chemical emission patterns, and on the other hand at another frequency band (i) to study the molecules via various rotational transitions spanning a range of energies, and (ii) to constrain the spectral index of the continuum in order to determine the nature of the proposed companions. On top of that, other ESO instruments such as GRAVITY and MATISSE of the Very Large Telescope Interferometer can provide crucial information about the dust location, and offer the potential for detecting the proposed companions. The ATOMIUM results will also stimulate many new radio observations of evolved stars with other interferometers or single antennas in the millimetre- and centimetre-wave domains (NOEMA, SMA, e-Merlin and large sensitive single antennas), for example to monitor masers using the Atacama Pathfinder EXperiment (APEX) (SiO) and Medicina, Pushchino and e-Merlin (22 GHz water). And although the ATOMIUM sources are bright in the infrared, the chronographic modes or off-source pointing offered by the NIRCAM and MIRI instruments on board the JWST should allow us to get high sensitivity infrared images of the stellar winds, similar to the recent Early Release Science data of the colliding wind Wolf-Rayet binary WR140 (Lau et al., 2022).

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Links

[1] The ATOMIUM project website: https://fys.kuleuven.be/ster/research-projects/aerosol/atomium
[2] ATOMIUM consortium members list: https://fys.kuleuven.be/ster/research-projects/aerosol/atomium/consortium-members

ALMA (ESO/NAOJ/NRAO)

A number of ALMA's 66 high-precision radio antennas can be seen in this image, connected by cleared pathways. The array spends its time observing the cool Universe and its phenomena — star formation, molecular clouds, stellar evolution, and the early Universe.

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The Fornax3D Survey — A Magnitude-Limited Study of Galaxies in the Fornax Cluster with MUSE

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The Fornax galaxy cluster is an ideal nearby laboratory in which to study the impact of dense environments on the evolution of galaxies. The Fornax3D survey offers extended and deep integral-field spectroscopic observations for the brightest 33 galaxies within of virial radius of the Fornax cluster, obtained with the MUSE integral-field spectrograph, mounted on Unit Telescope 4 (Yepun) of ESO's Very Large Telescope in Chile. The Fornax3D data allowed us to reconstruct the formation of early-type galaxies in the cluster and to explore the link with spiral galaxies. Results have been published in 19 refereed papers since 2018. In this paper we review the broad goals of this campaign, its main results and the potential for future studies combining the MUSE data with the abundant multi-wavelength data coverage for Fornax.

Background and goals of the Fornax3D survey

Galactic environment is one of the key drivers of galaxy evolution, with galaxies losing their ability to form new stars and gradually transforming from late-type to early-type objects as they transition to dense galaxy groups or clusters (for example, Dressler, 1980). Various mechanisms have been proposed to explain such a morphological transformation, from gravitational perturbations with other group or cluster members (for example, Moore et al., 1996) to hydrodynamic interactions with the hot and dense gas medium that permeates high-density regions (for example, Boselli & Gavazzi, 2006). The use of integral-field spectroscopy (IFS) has led to significant advances in our understanding of the environmental evolution of galaxies, directly as it happens for instance in ram-pressure stripped objects (for example, Poggianti et al., 2017) and indirectly through the detailed study of the structure of nearby early-type galaxies (ETGs) to infer how their morphological transition occurred, leading to their present kinematic divide between slow- and fast-rotating objects (Emsellem et al., 2007, 2011).

With its extended spectral range, fine spatial sampling, large field of view, and superb throughput, the MUSE integral-field spectrograph (Bacon et al., 2010) is a unique instrument with which to address these (and related) outstanding issues, as demonstrated by some of the first MUSE studies of both slow- and fast-rotating ETGs (Emsellem, Krajnovic & Sarzi, 2014; Guerou et al., 2016). This is particularly the case when MUSE data are combined with sophisticated orbit-superposition models (for example, Krajnovic et al., 2015), which already showed how fast-rotators indeed also contain a dynamically warm component resembling the thick disc of spiral galaxies (Zhu et al., 2018). At the same time MUSE has the potential to further explore the stellar population properties of stellar halos, following in the footsteps of earlier IFS investigations (Weijmans et al., 2009) and allowing a connection to be made with the increasing imaging constraints (for example, Iodice et al., 2016) and modelling predictions (for example, Cook et al., 2016). In this context, the Fornax cluster is an ideal laboratory in which to study the archaeological record of environmental processes using MUSE observations, thanks to its proximity (around 20 Mpc; Blakeslee et al., 2009), more characteristic intermediate cluster mass ($M_{vir} < 10^{14}\ M_{\odot}$; Drinkwater, Gregg & Colless, 2001), southern sky location and plethora of available ancillary data, ranging from optical Hubble Space Telescope (Jordán et al., 2007) and deep Very Large Telescope (VLT) Survey Telescope multi-band images from the Fornax Deep survey (Iodice et al., 2016) to millimetre-wavelength and radio data from the Atacama Large Millimeter/submillimeter Array (ALMA) and MeerKAT (Zabel et al., 2019; Serra et al., 2016) mapping the molecular and HI gas reservoirs of Fornax galaxies.

These considerations motivated the Fornax3D survey (Sarzi et al., 2018; Iodice at al., 2019b), which obtained deep and extended MUSE observations for all 33 galaxies within the virial radius of the Fornax cluster with an apparent *B*-band magnitude brighter than 15. The Fornax3D observations, totalling 106 hours of VLT time, reached a spectral signal-to-noise (S/N) ratio of 25 out to a *B*-band surface brightness of 25 mag. arcsec^{-2} after binning and a S/N of 100 within each central MUSE pointing with little or no binning. This allowed us to pursue the following main objectives: a) fully characterise the embedded discs of ETGs using both orbit-superposition dynamical models and high-quality stellar-population measurements; b) map in detail the stellar-population properties of ETGs, including constraining the slope of the low-mass end of the stellar initial mass function (IMF) and obtaining age and metallicity gradients for their stellar halos; c) provide a census of unresolved sources such a globular clusters and planetary nebulae; d) assess the impact of environmental effects on Fornax LTGs tapping also on ancillary data; and e) provide a rich dataset for the astronomy community.

The assembly history of the Fornax cluster

The increasing number of cosmological simulations dealing with the formation and evolution of galaxies has in recent years allowed the evolution of significant samples of simulated high-density environments to be followed (for example, Pillepich et al., 2018). Iodice et al. (2019b) improved the picture of the structure and assembly history of the Fornax cluster by combining measurements of the photometric, stellar-population and star-formation properties of Fornax galaxies from the Fornax Deep Survey (FDS; Iodice et al., 2016) images and the Fornax3D MUSE data, placing them in the context of numerical predictions of the phase-space distribution of galaxies in Fornax-like clusters.

This led to the identification of three well-defined structures in Fornax: the core, the north-south (NS) clump and the infalling galaxies (Figure 1, left panel). The core is dominated by the potential of the brightest cluster galaxy, NGC 1399, which coincides with the peak of the X-ray emission. The NS clump galaxies are the reddest, most massive and metal-rich galaxies in the sample, and few of them show ionised gas emission. The infalling galax-

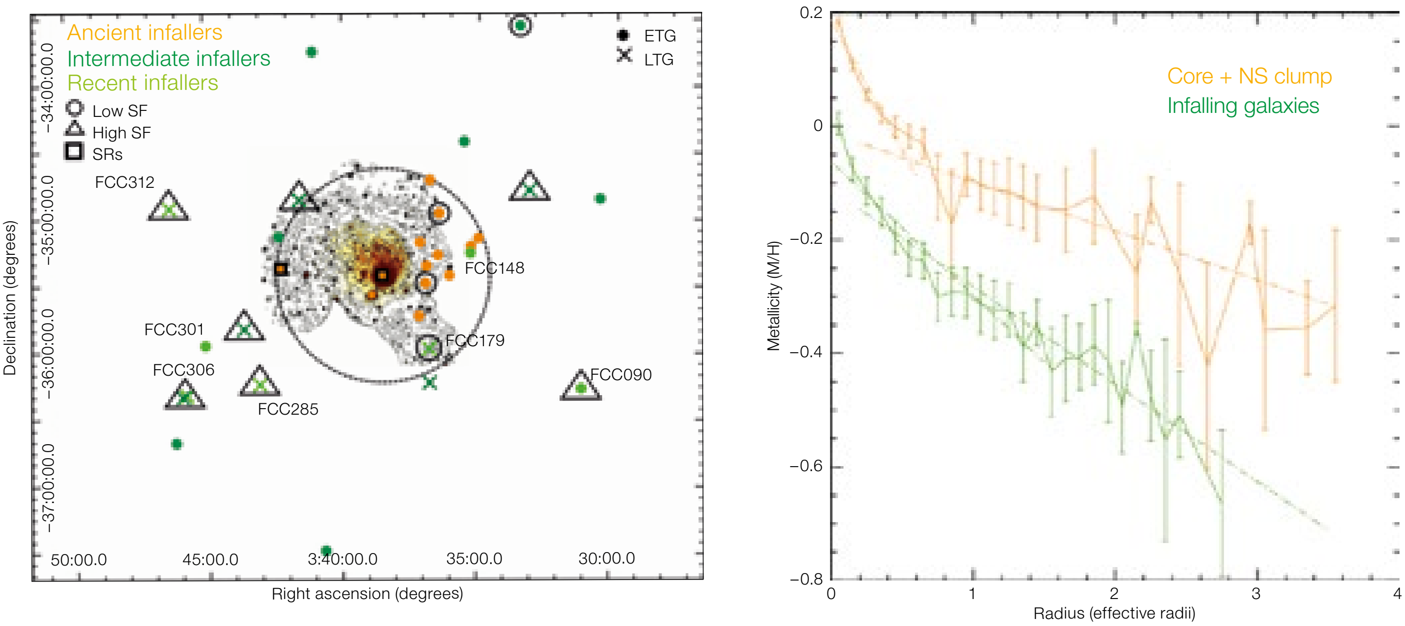

Figure 1. Left panel: Distribution of the Fornax3D sample ETGs (circles) and LTGs (crosses) on the sky. The right ascension and declination (J2000.0) are given in degrees on the horizontal and vertical axes, respectively. The background image and contours map the X-ray emission in the energy range 0.4–1.3 KeV as measured by XMM-Newton (Frank et al., 2013). The dashed circle indicates the transition from the high-density region to the low-density region of the cluster at 0.4 R_{vir} ~ 0.3 Mpc. Orange, green, and light-green symbols represent galaxies identified in phase-space as ancient, intermediate, and recent infallers, respectively, with the last of those being also individually labelled. Black open triangles and circles point to galaxies with high and low star formation activity, respectively, with open black squares further showing the only two slow-rotator ETGs in the Fornax3D sample. Right panel: Running mean as a function of radius of the azimuthally-averaged metallicity for the sample galaxies in the core-NS clump (orange symbols) and for those infalling in the Fornax cluster (green symbols), as also shown in the left panel. The dash-dotted lines represent the fits to the metallicity gradients between transition radii from the bounded in-situ inner component to the accreted ex-situ stellar halo (Spavone et al., 2020).

ies are distributed nearly symmetrically around the core, at larger projected distance than the galaxies in the clump. Most infalling galaxies are late-type galaxies (LTGs) with ongoing star formation, signs of interaction, a disturbed molecular gas (Zabel et al., 2019; Raj et al., 2019) and on average a lower stellar metallicity compared to objects in the NS clump.

Comparing the phase-space position of the Fornax3D objects to that of simulated galaxies (Rhee et al., 2017) confirms that the infalling galaxies are either intermediate or recent infallers that entered the cluster less than 4 Gyr ago. Conversely, all but one of the NS clump galaxies fall in the simulated loci of ancient infallers, indicating that the clump may have resulted from the gradual accretion of a group of galaxies more than 8 Gyr ago, most likely along the cosmic web filament connecting the Fornax-Eridanus large-scale structure.

Pushing into the halos of early-type galaxies

The phase-space segregation of galaxies in the Fornax cluster is also mirrored by systematic differences in the properties of their stellar outskirts. Taking advantage of the extended coverage and depth of the Fornax3D data, Spavone et al. (2022) derived the azimuthally-averaged radial profiles of the stellar velocity dispersion, inclination-corrected specific angular momentum, age, and metallicity for the non-central ETGs of the Fornax3D sample, out to distances of ~ 2–3 effective radii and well beyond the first transition radius, from the bounded in-situ component to the accreted (ex-situ) stellar halo, as previously derived by Spavone et al. (2020) using deep FDS images.

As shown in Figure 1 (right panel), galaxies in the core and NS clump of the cluster, which have the highest accreted mass fraction, show milder metallicity gradients in their outskirts than the galaxies falling into the cluster. This difference in outer metallicity gradients and accreted mass fraction between the galaxies in the two main Fornax sub-structures reinforces the idea that the NS clump may result from the accretion of a group of galaxies during the gradual build-up of the cluster, while the infalling galaxies entered the cluster later. Pre-processing mechanisms in the clump, such as repeated mergers, may indeed have been responsible for shaping the stellar halo around such galaxies, feeding this component in terms of baryonic mass and producing a mixing of different stellar populations from the accreted satellites that resulted in a flatter metallicity radial profile at larger radii.
On the other hand, the lack of an extended stellar envelope in the infalling galaxies is consistent with their steeper metallicity gradients.

State-of-the-art mapping of stellar population properties

The Fornax3D MUSE data cover an extended area of galactic discs in Fornax, on average out to two half-light radii, allowing our understanding of the formation of discs in ETGs to be tested.
In particular, high-quality two-pointing mosaics of the three edge-on lenticular galaxies in the Fornax3D sample pro-

vided a unique view of their vertical structure (Pinna et al., 2019a,b). In all three objects our stellar-population maps indicated the presence of an old, metal-poor thick disc with enhanced alpha-element abundances and of a more metal-rich but less alpha-enhanced thin disc. One galaxy, located close to the cluster centre, shows overall very old populations, probably due to a strong impact of star-formation quenching processes in both cluster and pre-cluster environments. On the other hand, the position of the other two galaxies in less dense regions of the cluster may have allowed a more prolonged star formation, resulting in younger ages for their thin disc. Spatially resolved star-formation histories for these edge-on objects also revealed the presence of younger and more metal-poor sub-populations in their thick discs, probably accreted during past mergers.

A more complete mapping of the stellar age, metallicity and alpha-element abundance across the sample was provided by Martín-Navarro et al. (2019, 2021), who exploited the exquisite quality of Fornax3D data to also map, for the first time, the two-dimensional variations of the IMF beyond the Milky Way (Figure 2). The IMF maps revealed a striking surprise: metallicity alone is not able to explain the complex behaviour of IMF variations, which appear also to be coupled to the internal orbital structure of galaxies (Poci et al., 2022).

Chemo-dynamical modelling dissection of early-type galaxies

Building on previous modelling efforts to dissect the stellar-population components of ETGs (for example, Zhu et al., 2018), we have developed new orbit-superposition techniques capable of matching simultaneously not only the observed stellar surface brightness and kinematics but also maps of the stellar age and metallicity as shown in Figure 2 (Poci et al., 2019; Zhu et al., 2020). By applying this to all 23 ETGs in the Fornax3D survey we obtain their internal stellar orbit distributions as well as their age and metallicity distribution, which we can use to separate different components in a physical and flexible way. Figure 3 (top panels) illustrates the case of FCC167, where we isolate a dynamically cold, metal-rich and relatively younger disc, a concentrated dynamically hot and metal-rich bulge, a more extended and metal-poor inner stellar halo and a dynamically warm component.

Using these models we derived several interesting results: (1) for the three edge-on galaxies in Fornax we derived the stellar age-velocity dispersion profile of their discs and found evidence that metallicity may be a key driver of this relation (Poci et al., 2021), making them directly comparable with high-redshift galaxies; (2) in the massive ETGs FCC 167 and FCC 276, we ascribed the formation of their inner stellar halo to a merger with a now-destroyed massive satellite (Zhu et al., 2022a,b), making it possible to in future quantify the timing and accreted mass during ancient massive mergers for large samples of nearby galaxies; and (3) we isolated the dynamically-cold disc of all Fornax3D ETGs and found that the galaxies that fell into the cluster early on have significantly lower cold-disc mass fractions than the recently infalling galaxies (Figure 3, lower panels) and that cold discs in ETGs have positive age gradients, supporting an outside–in quenching of their star formation while falling into the cluster (Ding et al., 2022, submitted to *Astronomy & Astrophysics*).

Zooming-in on globular clusters and planetary nebulae

Because of their old ages, globular clusters (GCs) are regarded as important fossil tracers of galaxy evolution. Fahrion et al. (2020a) used the excellent image quality of the Fornax3D data, with a median FWHM

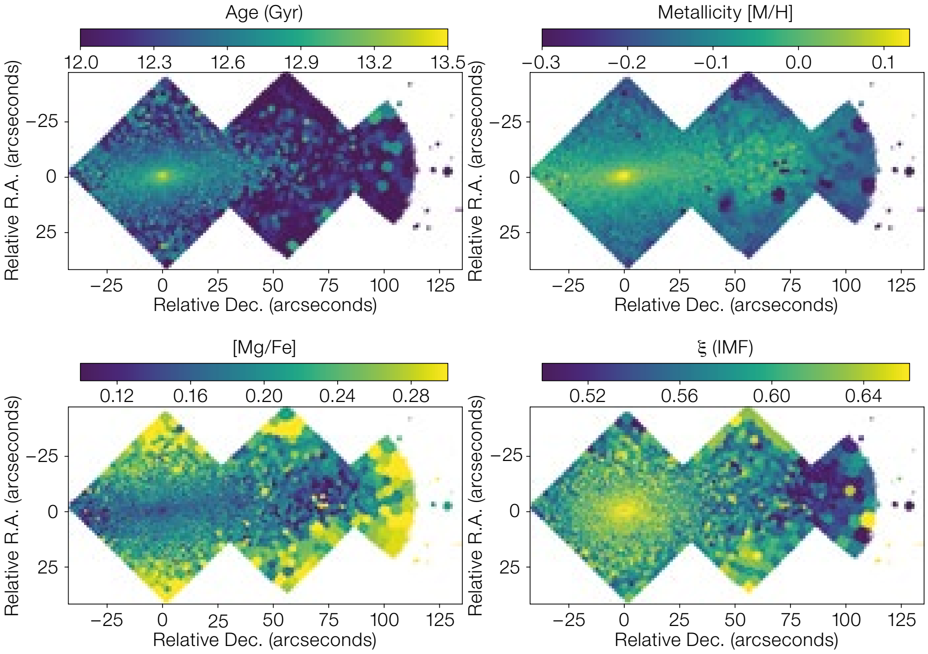

Figure 2. Stellar population maps of NGC 1380 (FCC167). Top left panel: age map where a relatively older central component is clearly visible. The metallicity (top right) and the magnesium abundance [Mg/Fe] (bottom left) maps show the clear signature of a chemically evolved disc, confined within a vertical height of ~10 arcsec, which coincides with the kinematically cold component observed in this galaxy. The stellar dwarf-to-giant ratio map (ξ, bottom right panel), which is tracing the variation of the initial mass function (IMF) over the field of view of the galaxy, exhibits a different 2D structure, however, that does not follow the metallicity variations, but closely follows the dynamically hot and warm stellar component revealed in this galaxy thanks to orbit-superposition models (Sarzi et al., 2018).

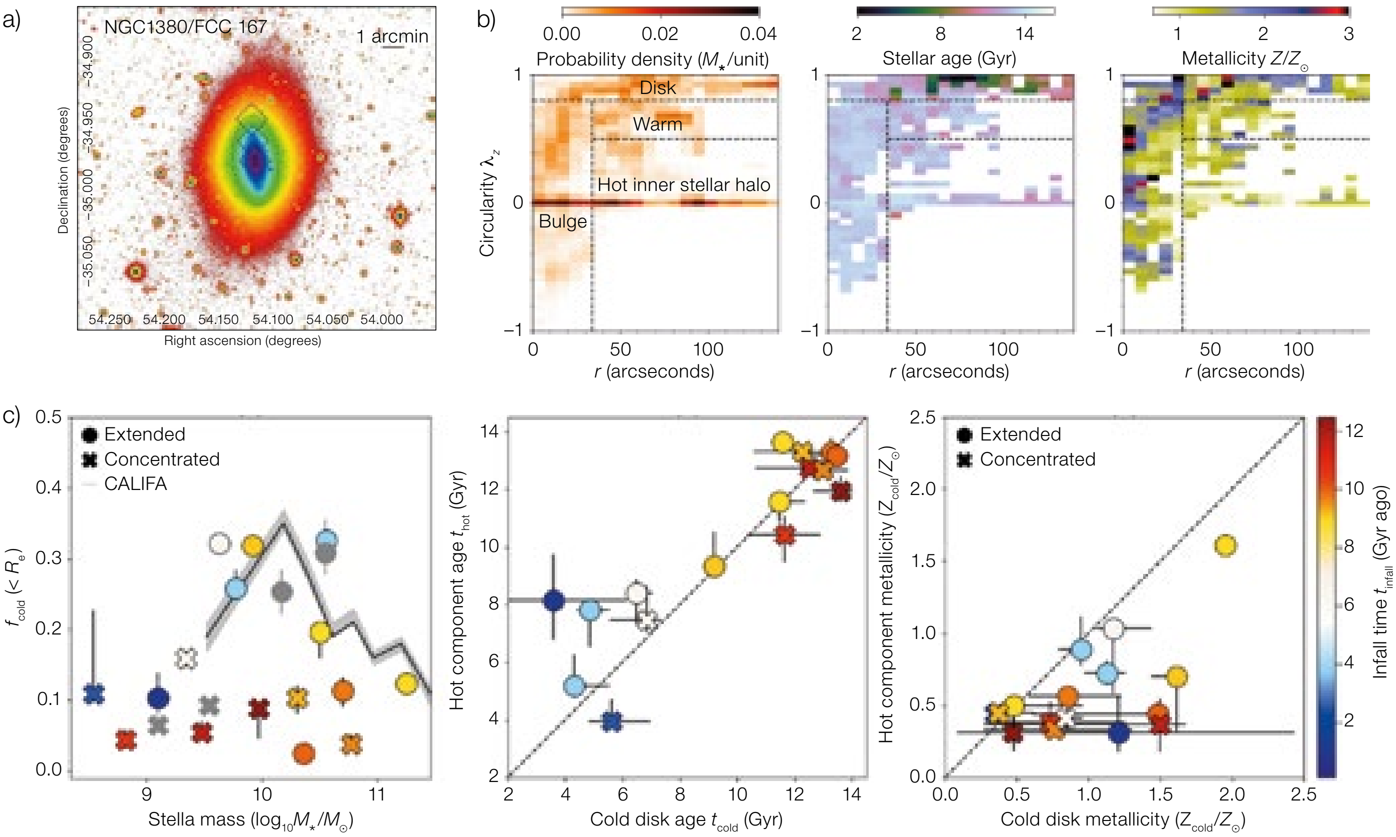

Figure 3. Panel (a): Deep r-band image of NGC 1380 (Iodice et al., 2019a). The three diamonds show the position of the Fornax3D MUSE pointings whereas the dashed black ellipse traces the isophote at a B-band surface brightness level of 25 mag arcsec^{-2}. Panels (b): Population-orbit superposition model results for NGC 1380. The left panel shows the probability density distribution of the stellar orbits p(r, λ_z) in the phase space of time-averaged radius r versus circularity λ_z in units of stellar mass per unit area in phase space, normalised to the total mass within the coverage of the MUSE data. The central and right panels show the stellar age $T(r, \lambda_z)$ and metallicity $Z(r, \lambda_z)$ distribution of the orbits in the same phase-space, respectively. Panels (c): Properties of the dynamically cold discs in the Fornax3D ETGs. The left panel shows the cold-disc fraction as a function of total stellar mass whereas the central and right panels compare the average stellar age and metallicity of cold discs to that of dynamically hot and warm components. In all three panels, galaxies are colour-coded according to their cluster infall time and shown with different symbols according to whether they are concentrated or extended. Galaxies that entered the cluster more recently tend to have extended and relatively more massive discs, which can also show younger populations. More generally stars in dynamically-cold discs tend to be more metal-rich, across the whole sample.

of 0.9 arcseconds, to extract and analyse the spectra of GCs even in the central regions of the Fornax3D sample galaxies. MUSE allowed us to accurately account for the background in each GC spectrum, collecting an extensive spectroscopic GC catalogue with 722 GC velocities and 238 metallicity measurements. Using this data set, we explored how well GCs trace the underlying galaxy properties and found GCs to be valuable tracers of the enclosed mass as well as the galaxy metallicity, from the central regions out to several effective radii. Additionally, we established a nonlinear relation between GC metallicities and photometric colours that has strong implications for the merger histories inferred solely from GC colours (Fahrion et al., 2020b).

Planetary Nebulae (PNe) are incredibly luminous sources of [OIII]λ5007 nebular emission that can be found across different galaxies and used to derive the distances to their host galaxies, thanks to the apparently invariant bright-end cut-off of the PNe luminosity function (PNLF; for example, Ciardullo et al., 1989). In this respect, integral-field spectroscopy can secure well-sampled PNLFs by making it possible to probe the central regions of galaxies that are indeed rich in PNe (for example, Sarzi et al., 2011; Kreckel et al., 2017). Spriggs et al. (2020, 2021) used the Fornax3D MUSE data to identify 1350 PNe across 21 ETGs, deriving PNLF distance measurements that agree well with previous distances based on surface brightness fluctuations (Blakeslee et al., 2009). With these individual measurements, we arrive at an average distance to the Fornax cluster itself of 19.86 ± 0.32 Mpc. These are encouraging results, considering the potential of adaptive-optics-assisted MUSE observations to push even further the reach of PNLF distance measurements.

Combining with ancillary data and the value to the Community

The value of the Fornax3D data increases further when they are used together with ancillary data, especially when studying the evolution of gas and dust in cluster

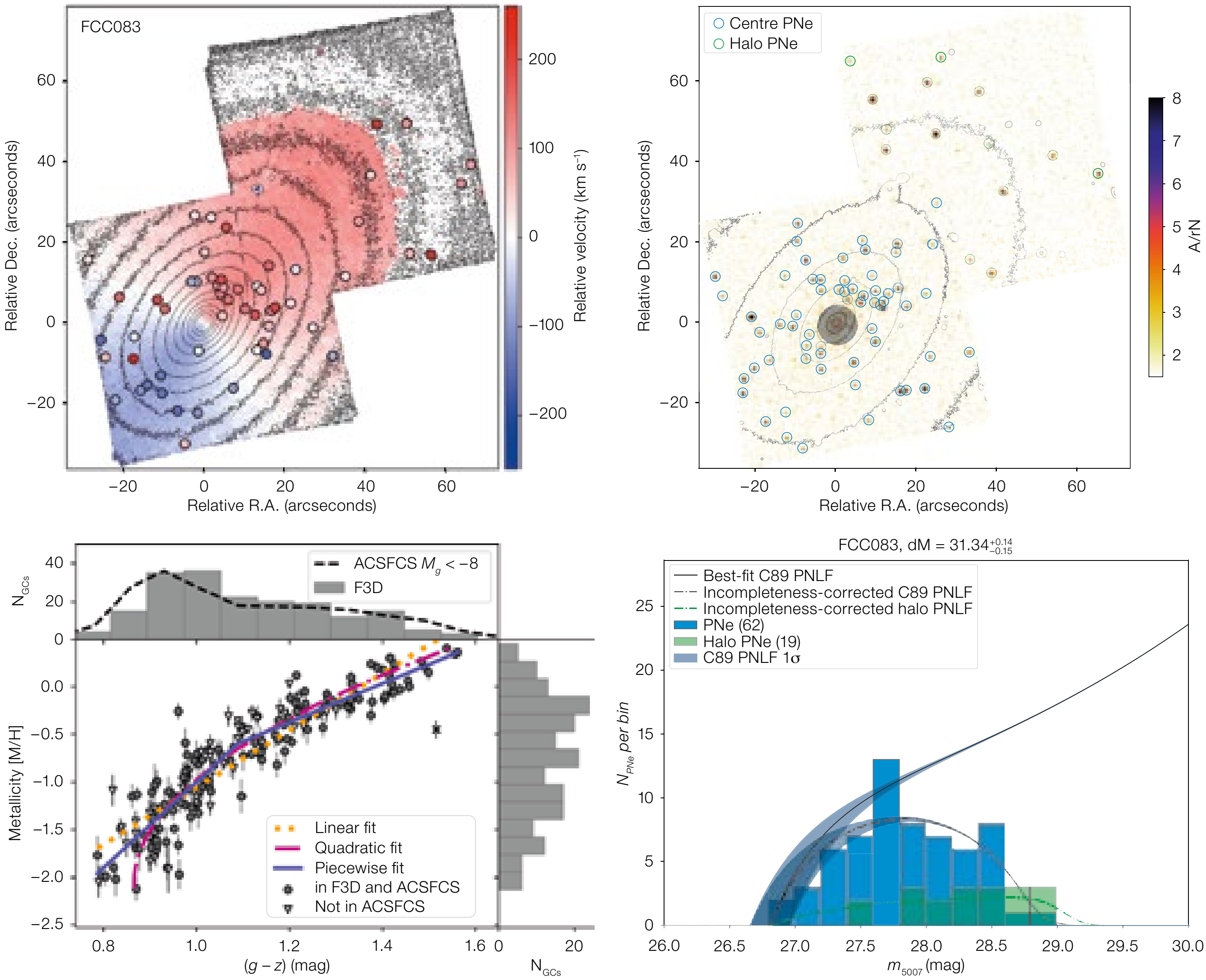

Figure 4. GCs and PNe in the Fornax3D galaxies. Left panels: MUSE stellar velocity for FCC083, with GCs detections and their velocities (top) and non-linear colour-metallicity relation of GCs across the entire sample (bottom). Right panels: Map of the the amplitude-to-residual noise ratio (A/rN) between the peak amplitude of the (OIII)λ5007 emission over the noise level in the residuals of our fit to the MUSE spectra showing the location of PNe point sources (top) and resulting PNLF for each MUSE pointing with corresponding fits fully accounting for PNe detection incompleteness and delivering the apparent magnitude of the bright cutoff (bottom).

galaxies. For instance, Viaene et al. (2019) combined MUSE measurements for the dust attenuation curve with radiative transfer models based also on Herschel, WISE and SPIRE data to conclude that the central dust disc of NGC1380 lacks small grains. At the same time, dust destruction timescales from sputtering based on Chandra X-ray data indicate that such dust must be strongly self-shielding and clumpy or else it would already have disappeared.

Using data from the ALMA Fornax Cluster Survey (Zabel et al., 2019) we further explored the depletion timescale for the gas reservoirs in 15 Fornax galaxies by comparing, on the scale of 300 pc, the MUSE extinction-corrected star formation rates with ALMA measurements for the molecular gas content. In this way we found that gas depletion times appear to shorten closer to the cluster centre, albeit that this trend is mainly driven by dwarf galaxies with disturbed molecular gas reservoirs (Zabel et al., 2020). In a second work, we derived the dust-to-gas ratio in Fornax galaxies, computed using far-infrared Herschel observations to measure the total dust mass and data from the Australia Telescope Compact Array (ATCA; Loni et al., 2021) to obtain the total neutral gas mass values in addition to the ALMA molecular gas mass. We compared these total dust-to-gas ratios to mean values for gas-phase metallicity obtained from the Fornax3D

MUSE data (see also Lara-López et al. [2022] for a spatially resolved study of the gas metallicity in such objects). We find that gas-to-dust ratios in Fornax galaxies are systematically lower than those in field galaxies at fixed metallicity. This implies that a relatively large fraction of the metals in these Fornax systems is locked up in dust, which is possibly due to altered chemical evolution as a result of the dense environment (Zabel et al., 2021).

To conclude, the Fornax3D data also have a legacy value that is already driving progress in unanticipated ways. A case in point is represented by the work of Smith (2020) who detected seven novae via the analysis of individual Fornax3D exposures taken several months apart.

Data Release

The data release of the Fornax3D survey through the ESO Science Archive Facility is foreseen for the first quartile of 2023. It will contain reduced and calibrated mosaics for all galaxies and will be announced in the ESO Science Newsletter.

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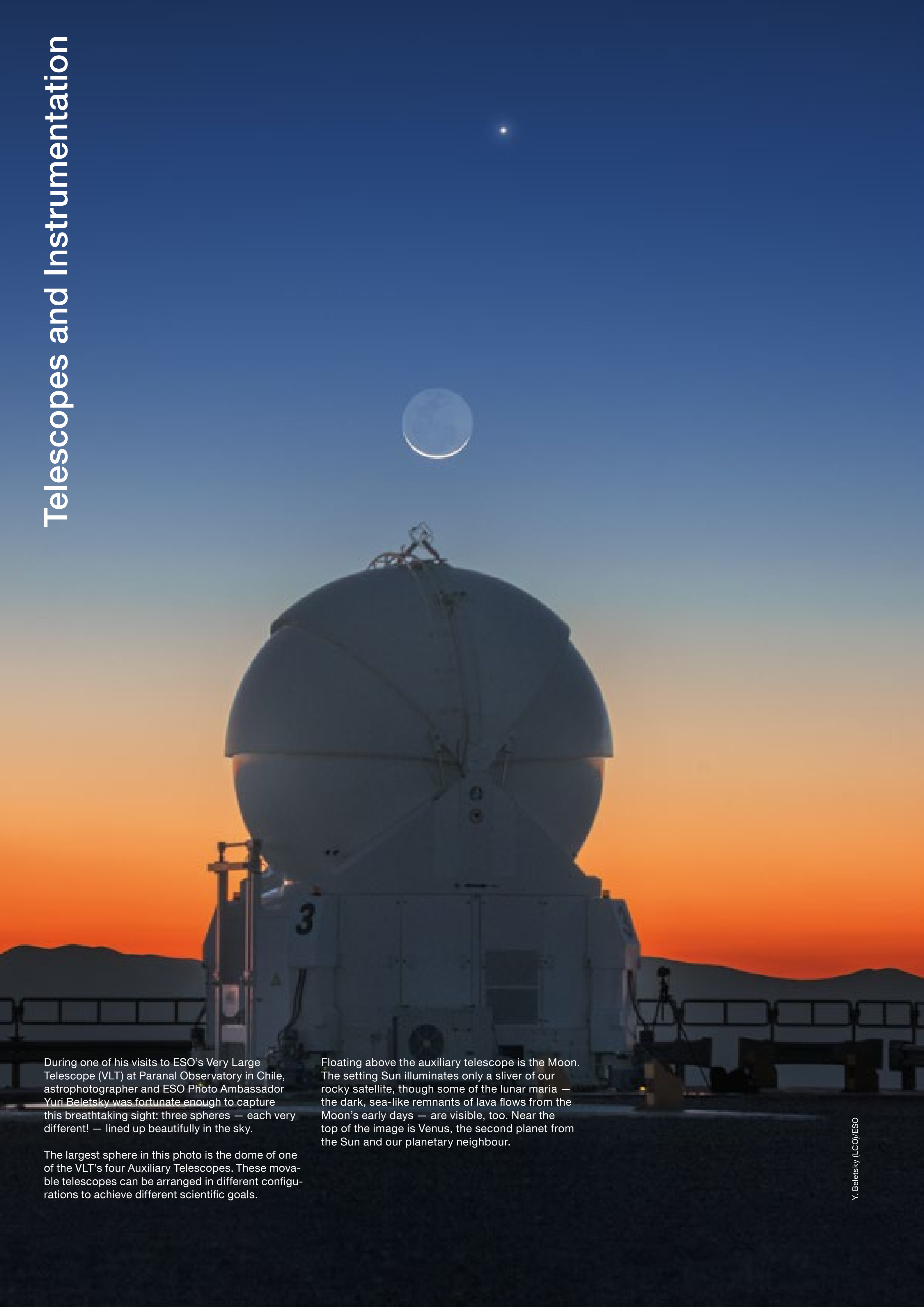
ESO/P. Horálek

A view from inside the planetarium at the ESO Supernova Planetarium & Visitor Centre, which opened its doors to the public on Saturday 28 April 2018. The building is open five days a week and features planetarium screenings, tours and a permanent exhibition in both German and English. The 25-degree tilted planetarium dome does not just give the audience the sensation of watching the Universe, but of being immersed in it.

This dramatic image of the galaxy Messier 83 was captured by the Wide Field Imager at ESO's La Silla Observatory, located high in the dry desert mountains of the Chilean Atacama Desert. Messier 83 lies roughly 15 million light-years away towards the huge southern constellation Hydra (the sea serpent). It stretches over 40 000 light-years, making it roughly 2.5 times smaller than our own Milky Way. However, in some respects, Messier 83 is quite similar to our own galaxy. Both the Milky Way and Messier 83 possess a bar across their galactic nucleus, the dense spherical conglomeration of stars seen at the centre of the galaxies.

Telescopes and Instrumentation



During one of his visits to ESO's Very Large Telescope (VLT) at Paranal Observatory in Chile, astrophotographer and ESO Photo Ambassador Yuri Beletsky was fortunate enough to capture this breathtaking sight: three spheres — each very different! — lined up beautifully in the sky.

The largest sphere in this photo is the dome of one of the VLT's four Auxiliary Telescopes. These movable telescopes can be arranged in different configurations to achieve different scientific goals.

Floating above the auxiliary telescope is the Moon. The setting Sun illuminates only a sliver of our rocky satellite, though some of the lunar maria — the dark, sea-like remnants of lava flows from the Moon's early days — are visible, too. Near the top of the image is Venus, the second planet from the Sun and our planetary neighbour.

Y. Beletsky (LCO)/ESO

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The GRAVITY+ Project: Towards All-sky, Faint-Science, High-Contrast Near-Infrared Interferometry at the VLTI

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The GRAVITY instrument has been revolutionary for near-infrared interferometry by pushing sensitivity and precision to previously unknown limits. With the upgrade of GRAVITY and the Very Large Telescope Interferometer (VLTI) in GRAVITY+, these limits will be pushed even further, with vastly improved sky coverage, as well as faint-science and high-contrast capabilities. This upgrade includes the implementation of wide-field off-axis fringe-tracking, new adaptive optics systems on all Unit Telescopes, and laser guide stars in an upgraded facility. GRAVITY+ will open up the sky to the measurement of black hole masses across cosmic time in hundreds of active galactic nuclei, use the faint stars in the Galactic centre to probe General Relativity, and enable the characterisation of dozens of young exoplanets to study their formation, bearing the promise of another scientific revolution to come at the VLTI.

Introduction

The near-infrared interferometric beam-combiner GRAVITY has been in operation at the Very Large Telescope Interferometer (VLTI) for five years (GRAVITY Collaboration et al., 2017). During that time GRAVITY has transformed optical interferometry by delivering ground-breaking results in studies of the Galactic centre, active galactic nuclei (AGN), exoplanets, and young stellar objects (see for example GRAVITY Collaboration et al., 2018a,b,c; GRAVITY Collaboration et al., 2019a,b). GRAVITY can achieve microarcsecond astrometry and detect stars as faint as 20th *K*-band magnitude in the Galactic centre. The current performance is not the ultimate within reach, which motivated the upgrade of the instrument to GRAVITY+. Studies of the performance of the VLTI also highlighted the importance of infrastructure upgrades to increase the overall sensitivity (Mérand, 2018).

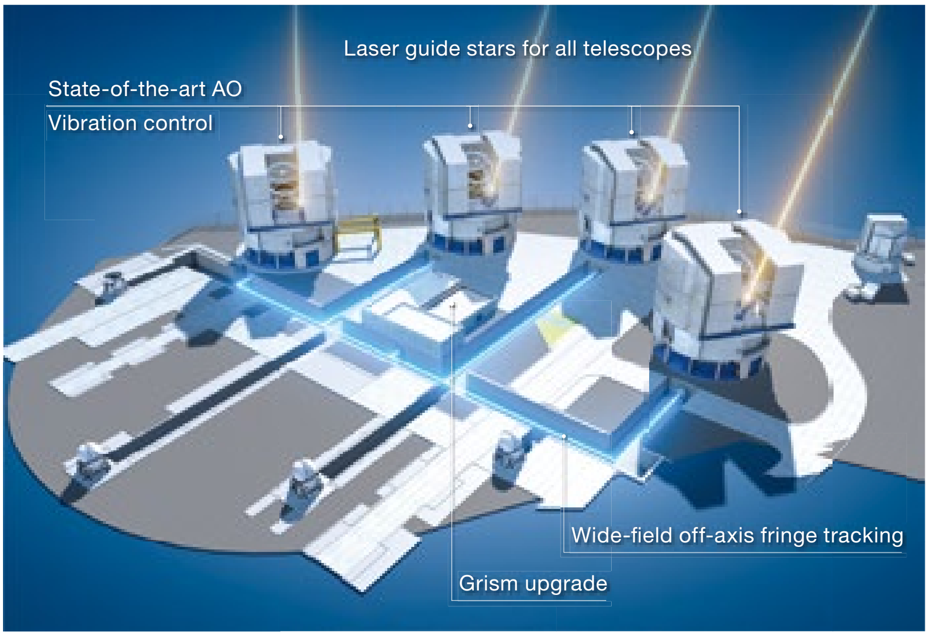
Following this, GRAVITY+ was first presented in 2019, and after a phase A study in 2021 the ESO Council approved the project in December 2021. Since then the phased implementation of GRAVITY+ has already started and is combining upgrades of the GRAVITY instrument and of the VLTI infrastructure itself. In its final form, GRAVITY+ will provide much better sensitivity, by adding state-of-the-art adaptive optics (AO) systems and laser guide stars (LGS) to all four Unit Telescopes (UTs) of the VLTI, and increase the field for picking a phase reference star from the current 2 arcseconds to 30 arcseconds for significantly improved sky coverage. Most of the upgrades serve all current and future VLTI instruments, in addition to GRAVITY itself.

Upgrades

Adaptive optics and laser guide stars upgrade

The need for a bright AO guide star and the limited performance of the current MACAO system on the UTs strongly limit the sky coverage with AO, and thereby interferometry at the VLTI. This limitation is addressed in GRAVITY+ by adding LGS and a new AO system to be installed on all UTs. GRAVITY+ will equip UT1, 2, and 3 with a side-launch LGS, the design of which is shared with the ESO's Extremely Large Telescope's LGS, and use one of the already existing Adaptive Optics Facility 4LGSF on UT4 (see Figure 1). The new state-of-the-art AO includes new wavefront sensors equipped with a natural guide star (NGS) and an LGS module each, with a high-order Shack-Hartmann sensor and a 1353-actuator deformable mirror. These new AO systems will dramatically increase the Strehl ratios and thereby the flux injection into the optical fibres of GRAVITY. Especially for faint targets, the improved AO will yield a flux increase in the fibre by up to a factor of 10. Furthermore, the new AO system will improve operability by reducing the demand for the very best atmospheric conditions for faint interferometry. In NGS operation the expected Strehl ratio for bright objects is greater than 80 % in the *K* band, and in LGS operation the expected limiting magnitude is $R = 18$ mag with a *K*-band Strehl of more than 40 %. With the improved AO performance, the limiting magnitude of the fringe-tracking star improves from currently $K \sim 10$ mag to $K = 13$ mag. The probability of finding such a fringe-tracking star within 30 arcseconds is almost 100% in the Galactic plane and remains above 25% for Galactic latitudes of 40° (Figure 2).

Figure 1. Overview of all GRAVITY+ components.



Off-axis fringe tracking

GRAVITY's highest sensitivity is achieved in the dual-beam mode, in which a nearby star is used for fringe tracking instead of the science target itself. In GRAVITY the separation between the science object and the fringe-tracking star has to be smaller than 2 arcseconds for the UTs and 4 arcseconds for the ATs, which significantly limits the number of observable targets. To overcome this limitation, one part of GRAVITY+ is the new off-axis fringe-tracking mode, called GRAVITY-Wide (GRAVITY+ Collaboration et al. 2022). In this mode, two subfields of the telescope field of view are selected by the star separators located at the coudé foci of the telescopes. One of the two fields contains the science source and the other one the fringe-tracking star. The two fields are brought separately into the VLTI lab and then both fields are fed into the GRAVITY beam-combiner. This mode allows much larger separations between the two objects than were previously possible. Separations of up to several tens of arcseconds are possible, effectively limited only by the coherence loss in the atmosphere, induced by the differential piston. GRAVITY-Wide is already fully commissioned and available to the community (GRAVITY+ Collaboration et al. 2022). Together with the LGS system this new mode significantly improves the sky coverage, as shown in Figure 2.

Sensitivity

GRAVITY+ also encompasses several other projects to increase the sensitivity of the instrument and reduce existing noise sources. In October 2019 two grisms were replaced in GRAVITY's science spectrometer. This upgrade yielded an improvement of a factor of 2–3 in throughput in the medium- and high-resolution modes (Yazici et al., 2021).

Another goal of this project is to reduce optical path differences (OPDs) in the VLTI. These OPDs come mainly from vibrations in the telescopes and affect the performance of the fringe tracker in GRAVITY. The upgrade of the vibration control system MANHATTAN2 is currently being commissioned at Paranal, to measure and compensate for existing high-frequency vibrations. Together with a new implementation of the fringe tracker, this will lead to a much improved fringe-tracking performance.

Finally, one of the main noise sources in GRAVITY is the back-fluorescence of the metrology laser into the spectrometer, which originates in the optical fibres of GRAVITY. Within GRAVITY+, we are developing new observing modes for the faintest targets in which the noise from the metrology laser is removed without losing the stability of the instrument (Widmann et al., 2022), by toggling the brightness of the laser beams between exposure times and presets.

Phased Implementation

The implementation of GRAVITY+ encompases three phases. The first phase is almost concluded, with the upgrade of the GRAVITY grisms and the implementation of the off-axis fringe-tracking mode already finished. Other parts of this phase, such as the improved fringe tracker implementation and the reduction of vibrations, are currently ongoing. The second phase of the project will see the replacement of the MACAO AO system with the GRAVITY+ AO system. In the last phase, which will conclude the GRAVITY+ implementation, the three remaining UTs will be equipped with LGS. The full project is expected to be completed and available to the community in 2026. The phased approach has the advantage that the upgrades have minimal impact on the normal VLTI operation while adding new capabilities at each step.

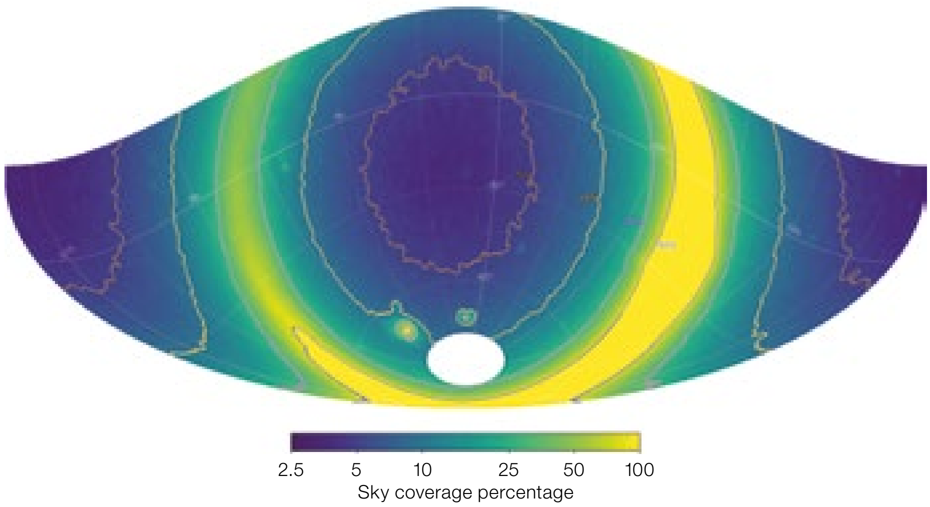
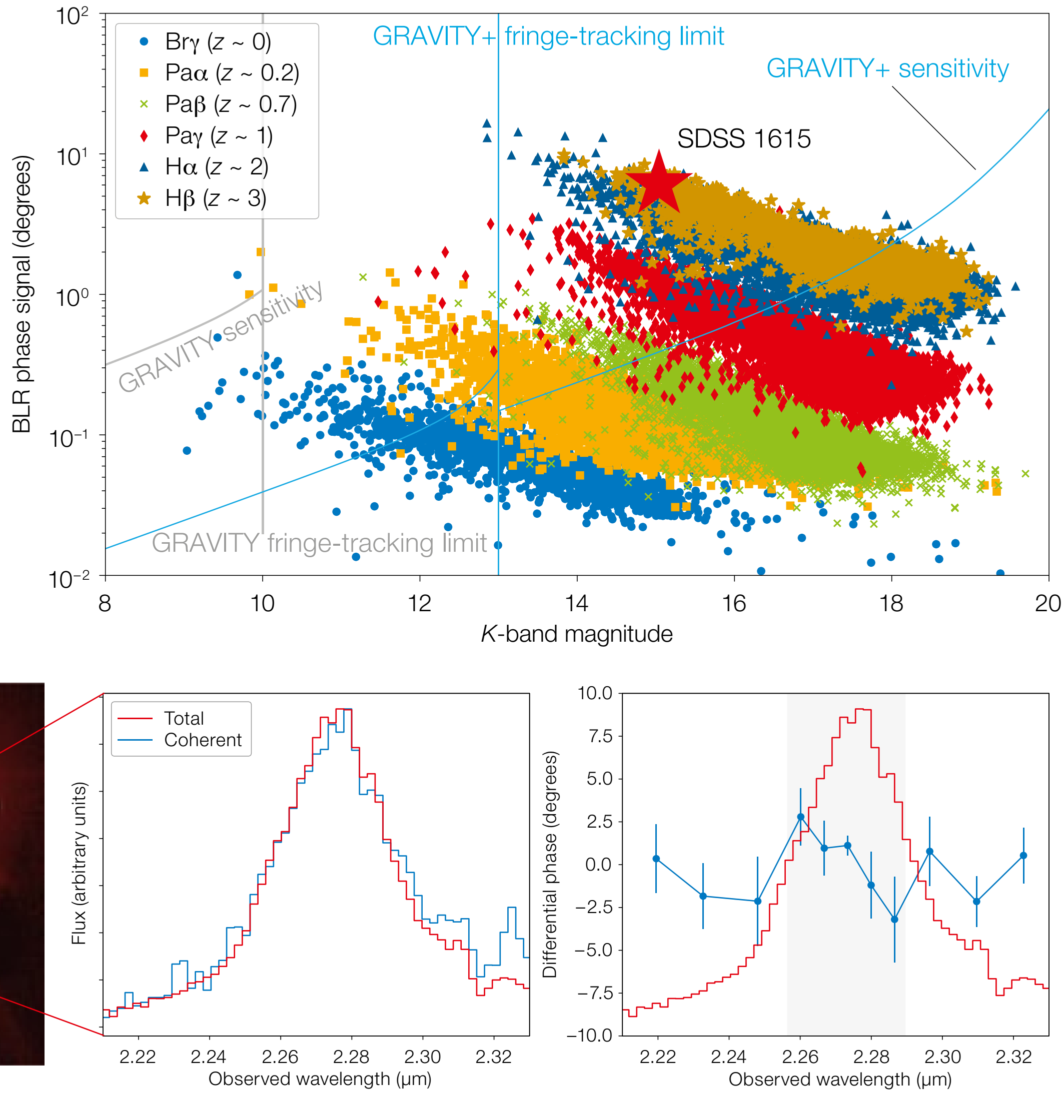


Figure 2. Sky coverage for LGS AO-supported off-axis fringe tracking with a fringe-tracking star as faint as m_K = 13, and a maximum allowed separation of 30 arcseconds. The sky projection is centred on the zenith in the Chilean spring. Areas not observable by the VLTI are left blank. This sky coverage is orders of magnitude larger than the current capability of the VLTI.

Science goals

AGN at high redshift

Supermassive black holes (SMBHs) are expected to be present at the centres of all massive galaxies in the Universe. The properties of the black holes are tightly correlated with the properties and evolution of their host galaxy. Crucial to understanding this co-evolution of the SMBHs and their galaxies is knowing the masses of the black holes. Especially for AGN, one cannot measure black hole masses directly but has to use indirect methods, combining velocity information from the AGN spectra with size information typically based on scaling relations that are calibrated via reverberation mapping (Peterson et al., 2004). However, spectroastrometry with GRAVITY can directly measure the sizes of the broad-line regions around SMBHs (GRAVITY Collaboration et al. 2018c). From the size measurement of the broad-line



region, one can directly infer the mass of the black hole. The sample of AGN currently within reach of GRAVITY is limited by the ability to fringe track on the AGN itself and the performance of the AO, leaving only a few AGN observable. With up to 30-arcsecond separations for external fringe tracking and significantly improved sensitivity, GRAVITY+ will increase the number of accessible AGN to a few 100, making it a true cosmic explorer (see Figure 3).

Measurements of SMBH masses around $z = 2$ are especially interesting as this was the peak of star formation in the Universe, which makes it a crucial time for the co-evolution of galaxies and their SMBHs. With the commissioning of GRAVITY-Wide, we could for the first time demonstrate the ability to observe a $z > 2$ AGN. As shown in Figure 3 the coherent flux of the AGN is clearly detected. This target was observed for only a little more than one hour, but we could already extract a tentative signal in the differential phase (for more information, see GRAVITY+ Collaboration et al. 2022).

Figure 3. Top: Observable AGN with GRAVITY+. At different redshifts, different spectral lines are observable in the *K* band, indicated by different colours. The observing limits in terms of fringe-tracking brightness (vertical line) and sensitivity (diagonal line) are shown for GRAVITY in grey and GRAVITY+ in blue. Targets fainter than the fringe-tracking limit will still be observable via GRAVITY-Wide. Bottom: The first successful observation of a high-redshift AGN with near-infrared interferometry. The left panel shows the target on the acquisition camera, which is indicated as an asterisk in the top plot. The right two panels show the coherent flux (middle) and the differential phase signal (right) from the AGN.

The Galactic centre

By observing stars orbiting the SMBH Sgr A* in the Galactic centre, GRAVITY has delivered precision tests of Einstein's general theory of relativity. In the orbit of the star S2, the effects of the gravitational redshift and the Schwarzschild precession have been observed (GRAVITY Collaboration et al. 2018a & 2020a). Together with the observation of material orbiting the central source close to the innermost stable orbit (GRAVITY Collaboration et al. 2018b), these observations have delivered the strongest evidence to date that Sgr A* is indeed a Schwarzschild-Kerr black hole. With its increased sensitivity and Strehl ratio GRAVITY+ will open up new possibilities in the Galactic centre. One is the search for fainter stars on close orbits around Sgr A*. The faintest star found with GRAVITY so far has a magnitude of $K > 19$ mag (GRAVITY Collaboration et al. 2022, and see Figure 4), but even fainter stars are expected to surround Sgr A*. Such a faint star on a close orbit would allow for the first time the measurement of the effects of the black hole's spin in a stellar orbit. A measurement of the spin would help to understand the accretion physics of massive black holes in a main-sequence disc galaxy and the interplay between Sgr A* and the accretion flow surrounding it. GRAVITY+ will be crucial for getting the astrometric accuracy needed to measure the effect of the spin on a star in the close neighbourhood of Sgr A* (see Figure 4). These observations will be complementary to the spectroscopic measurements with ERIS on the VLT and MICADO on the ESO's Extremely Large Telescope.

Not only will the detection of fainter stars be possible with GRAVITY+, but also the observations of flare motions and their polarisation properties will vastly improve. This will allow a better understanding of the magnetic field structure and hot gas motion on the innermost stable orbit around Sgr A* (GRAVITY Collaboration et al. 2018b). This would, for example, allow a test of whether for ultra-low-accreting black holes the spin of the black hole and the angular momentum vector of the accretion flow align via the Bardeen-Petterson effect (Bardeen & Petterson, 1975). Current simulations suggest that this should not be the case (Ressler, Quataert & Stone, 2018).

Exoplanets

The unique observing capabilities of GRAVITY have delivered the first characterisation of an exoplanet atmosphere in the K band with interferometry (GRAVITY Collaboration et al. 2019a), and astrometry with better than 50-microarcsecond accuracy, a factor of 50–100 more precise than conventional imaging techniques. These observations allow for the characterisation of young planets in the ice-line region at 2–3 au orbital separation from the host star, probing the location where these planets form (GRAVITY Collaboration et al. 2020b; Wang et al., 2021). The dramatic increase of AO performance with the high-order AO of GRAVITY+ will extend the inner working angle 5–8 times closer to the star than traditional direct-imaging instruments. The upgraded performance of GRAVITY+ will open up new parameter space for the exoplanet population, increasing the sample of directly imaged exoplanets by an order of magnitude. Precise host-star astrometry with GAIA will be a prime technique for determining prior estimates of where GRAVITY can search for planets, generating a large sample of observable planets in the 1–2 au region. This was recently demonstrated for HD 206893 c (Hinkley et al., 2022). The simultaneous measurement of luminosity with GRAVITY+ and masses with GAIA will enable the measurement of the mass-luminosity relation for dozens of planets, and thus constrain the initial entropy of these objects, which is key for understanding their formation. In addition, GRAVITY+ will be able to measure the atmospheric properties of gas-giant planets with significantly higher sensitivity, particularly the C/O ratio, which constrains the location and time of formation for these planets. Finally, the astrometric precision of GRAVITY+ will provide measurements of orbital architectures and dynamics of exoplanetary systems with unmatched precision, even in the era of extremely large telescopes, as already demonstrated with GRAVITY (Lacour et al., 2021).

Further science cases

In addition to the science cases mentioned here, the increased capabilities of GRAVITY+ will benefit many other observations. The increased sensitivity and sky-coverage of GRAVITY+ will enable the observation of embedded, low-mass young stellar objects at the onset of

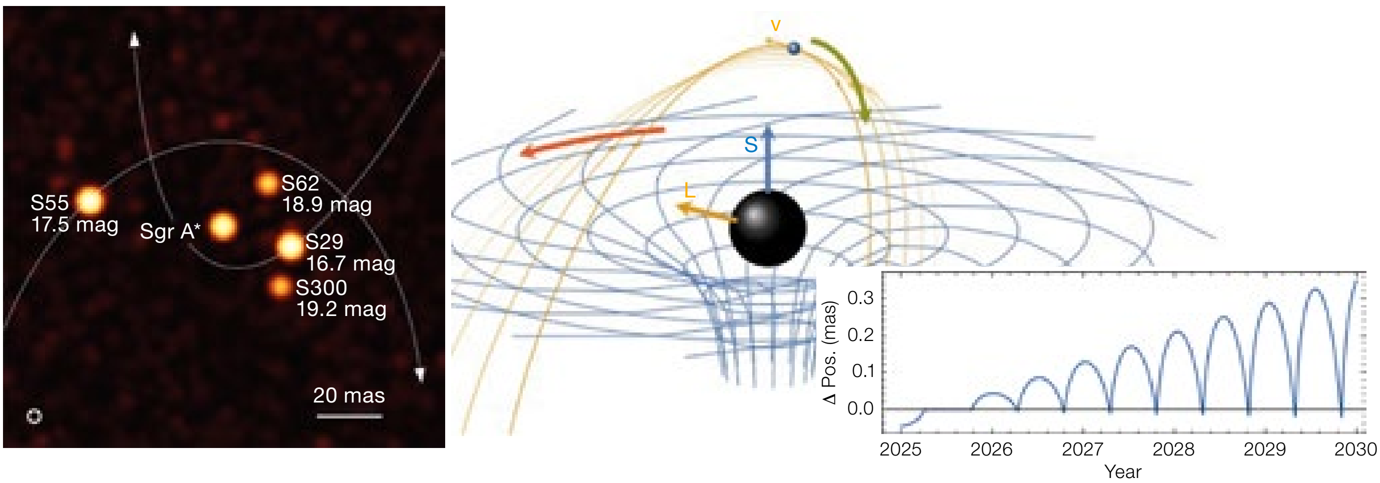


Figure 4. Left: Image of the stars around Sgr A* taken with GRAVITY. Right: Illustration of the Lense-Thiring precession of a star caused by a spinning black hole. The insert shows the effect on a hypothetical star with a semi-major axis ten times smaller than that of S2.

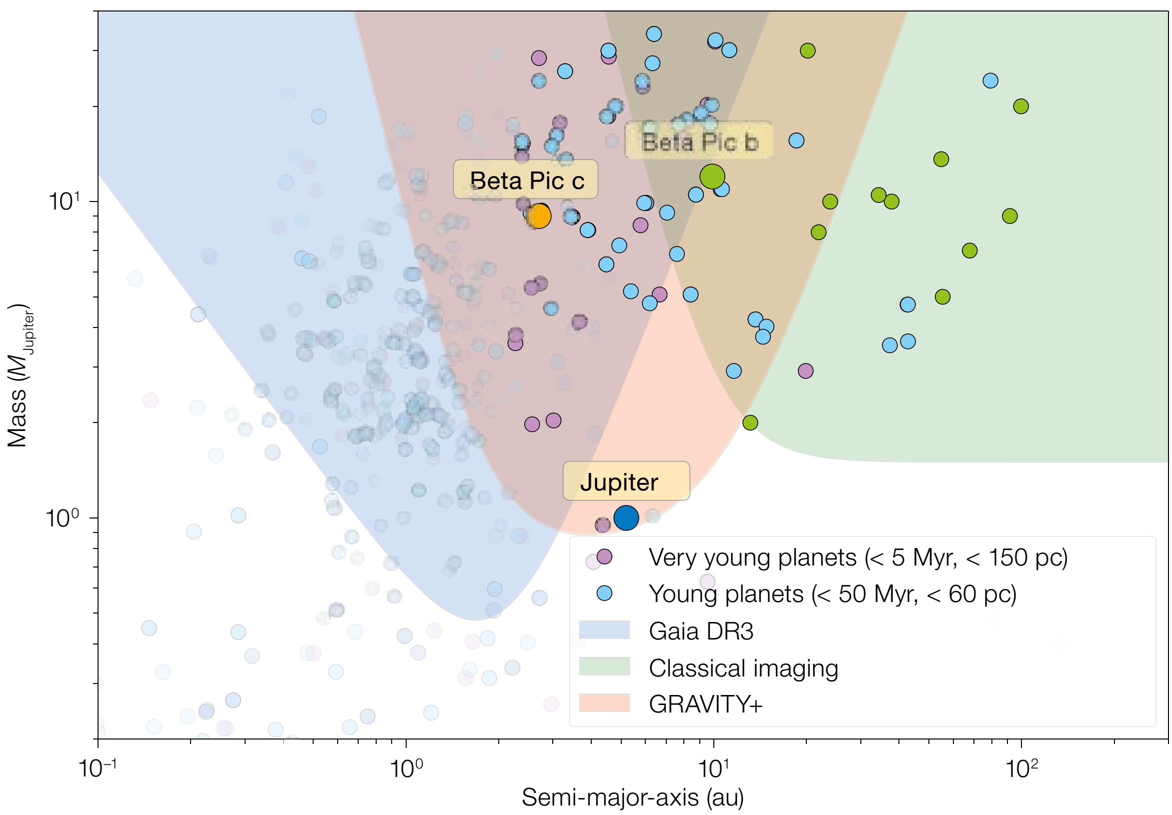


Figure 5. Exoplanet population as a function of semi-major axes and masses. GRAVITY+ will give access to a new part of the parameter space for young planets in the 1–10 au range. Potential GRAVITY+ detections are indicated by solid points.

planet formation. GRAVITY+ will be able to trace accreted and ejected gas, spatially resolved at a few stellar radii (Gravity Collaboration et al. 2020c). GRAVITY was also used to characterise compact objects via microlensing (see, for example, Dong et al., 2019). While only a few such events are within reach for GRAVITY, the upgrade will give access to thousands of microlensing events. Similarly, GRAVITY+ will permit resolving massive stars and searching for intermediate-mass black holes in globular clusters from precise tracking of stellar motions. The variety of different fields shows that GRAVITY+ is indeed an upgrade that will enable many new and unique science cases.

Conclusion

The GRAVITY instrument has transformed near-infrared interferometry. GRAVITY+ will continue to reshape this field with a major upgrade of the GRAVITY instrument and the VLTI infrastructure, thus also serving other VLTI instruments. The biggest leap will come with the implementation of a state-of-the-art AO system with LGS. GRAVITY will greatly benefit on many fronts from the improved AO system as it ensures a more stable flux injection into the optical fibres, which means a more stable fringe-tracker performance and a higher sensitivity for fainter targets. Together with the off-axis fringe-tracking mode, this will lead to a dramatic increase in sky coverage for GRAVITY+. With all the improvements GRAVITY+ will show an overall improvement in performance of 4–5 magnitudes and push the limiting magnitude down to approximately K = 22 mag. These performance improvements will lead to new and unique scientific opportunities. With the observation of galaxy and SMBH co-evolution around cosmic noon, the possible measurement of the spin of a SMBH, and the detection and characterisation of exoplanets in an otherwise unprobed regime, GRAVITY+ will stay at the frontier of astronomy. The combination of 8-metre-class telescopes at the VLTI and a highly sensitive interferometer itself is unmatched in the world. GRAVITY+, with its unique and timely scientific opportunities, ensures that the VLTI will deliver otherwise impossible scientific results and that it remains unique, even in the era of the 30–40-metre-class telescopes.

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Since 2005 ESO has been working with its community and industry to develop an extremely large optical/infrared telescope. ESO's Extremely Large Telescope, or ELT for short, is a revolutionary ground-based telescope that will have a 39-metre main mirror and will be the largest visible and

infrared light telescope in the world. To address specific topics that are needed for the science operations and calibrations of the telescope, thirteen specific working groups were created to coordinate the effort between ESO, the instrument consortia, and the wider community. We describe here the goals of these working groups as well as their achievements so far.

Background

In September 2019, ESO's Extremely Large Telescope[1] (ELT) Programme Scientist Michele Cirasuolo, in discussion with several members of the community, as well as the principal investigators of the first-generation ELT instruments (MICADO, MORFEO, HARMONI, and METIS), initiated the formation of a set of working groups (WGs) that had as their main goal the improvement of several critical elements needed by the ELT and its instruments to do transformative science and operate smoothly. These WGs bring together expertise from within ESO, the instrument consortia, and the wider community, with the aim of avoiding redundancy across the consortia, given that many of the issues dealt with are common to all instruments.

At present there are thirteen active WGs (Figure 1), each with its own coordinator(s) and with about 160 contributing members. The overall coordination and the inter-WG deliverables are led by Paolo Padovani (who has replaced Remco van der Burg), and Michele Cirasuolo. The ELT WGs work through various communication channels, including mailing lists, tWiki, Slack, MS Teams, and Zoom. ELT WG meetings have also been held yearly since May 2020.

The ELT WGs are open to the community and volunteers are very welcome. If you are interested in contributing to any of these WGs please contact Paolo Padovani or Michele Cirasuolo[a].

This article introduces the ELT WGs and highlights their main objectives and the results obtained so far.

Astro-weather (coordinators: Julien Milli and Angel Otarola)

The goal of the Astro-weather WG was twofold. In the first place, it identified the meteorological and atmospheric variables to be monitored, taking into account the requirements of the telescope and each ELT instrument. All these variables were discussed and ranked in three categories according to their priority. In a second step, the WG identified the sensors or technological solutions that could be used to monitor these relevant meteorological and atmospheric variables. This helped to make an estimate of the cost to purchase, and/or design and produce, these sensors. Ultimately, a report was produced summarising all the information gathered by the WG on the requirements for the ELT Astronomical Site Monitor (ASM), including priorities and an estimation of the required budget.

The astro-weather information, to be produced by the various systems comprising the ASM, is essential for the ELT and its instruments to work efficiently, as well as providing important input to other WGs, as shown in Figure 1. Weather data (temperature, relative humidity, wind speed and direction) are relevant to supporting the day and night operations and are therefore considered high-priority. The same is true for turbulence data (seeing, coherence time, isoplanatic angle, and high-resolution profiles of the surface layer turbulence and outer scale) that are used to predict the image quality, to help rank and schedule the science observations, and also to optimally extract the signal (point spread function [PSF] reconstruction: see below). Monitoring the precipitable water vapour is also considered a high priority, to support observations in the infrared (IR) and provide key observations for telluric line corrections (see below). The ELT's main mode of operation will be Service Mode supported by an adaptive queue scheduling of the science observations, and consequently monitoring of the sky transparency also becomes an important factor, as well as forecasting the weather, atmospheric turbulence, and precipitable water vapour on various timescales of interest.

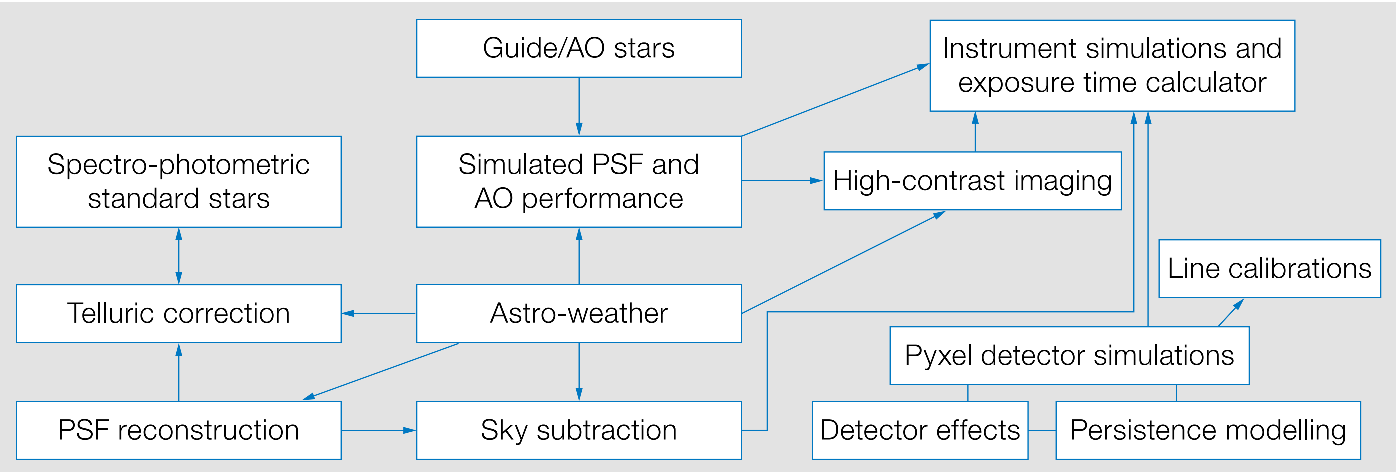

Figure 1. The diagram shows how the different ELT WGs are closely connected, with the output from any given WG feeding directly into (an)other WG(s).

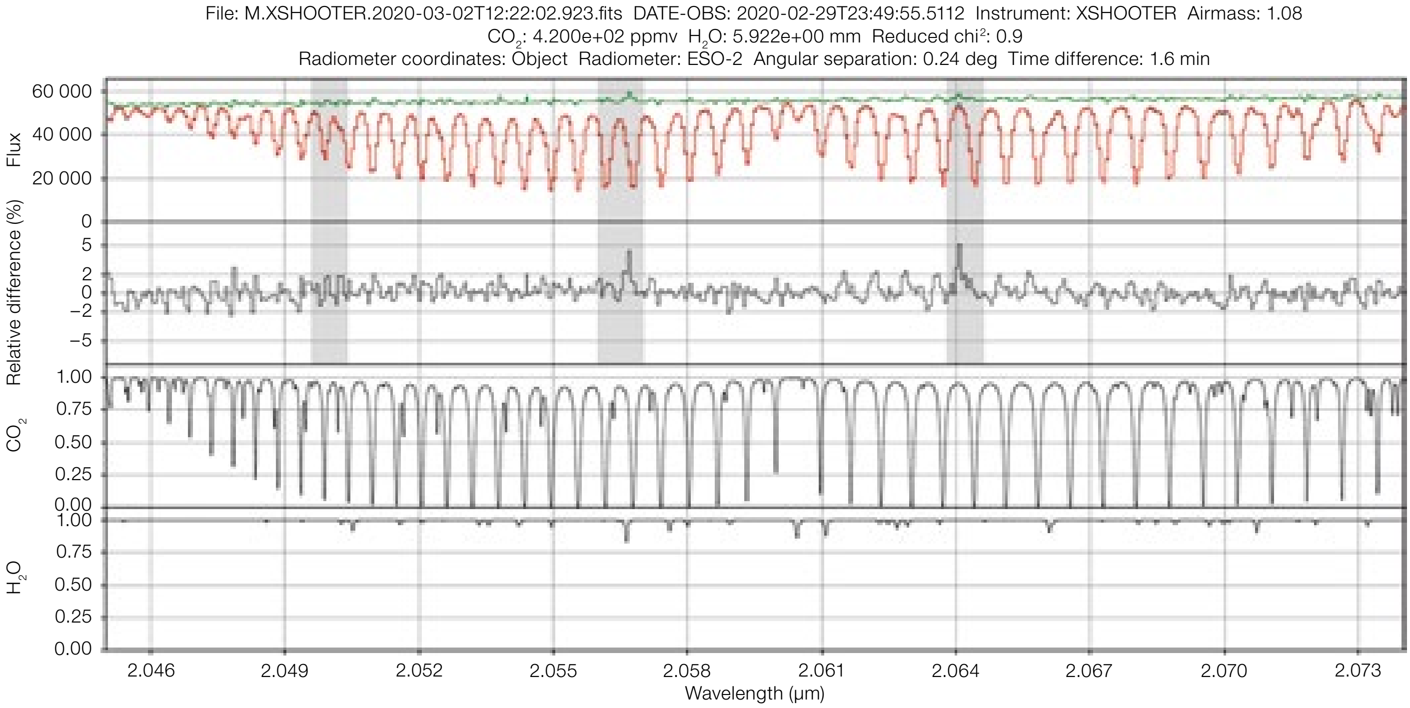

Figure 2. Example of telluric correction of an X-shooter telluric standard spectrum. The top graph shows the X-shooter reduced spectrum retrieved from the science archive in black, the best model obtained by Molecfit in red, and the ratio of the two in green. Data points in the grey area were not used for the fit owing to data quality issues affecting some spectra in a set of several hundred used for the CO_2 determination. The bottom two graphs show high-resolution reference (not fitted) spectra for CO_2 and H_2O. The free parameters of the model include the constants of a 1st-order Chebyshev polynomial for improving the wavelength calibration, the FWHM of a Gaussian profile for the line spread function, and the constants of a 1st-order polynomial representing the continuum. The temperature and humidity profiles (hence, the amount of precipitable water vapour) were obtained at 2020-02-29T23:48:16 with the ESO-2 radiometer, while the relative abundance of CO_2 relative to the reference atmospheric model was determined as the mean value of 16 measurements obtained over the month preceding the observations.

Telluric line correction (coordinator: Alain Smette)

A top-level requirement for the ELT instruments is to minimise nighttime calibrations. However, an IR spectrum displays telluric absorption lines arising from Earth's atmosphere. Their correction usually requires observation of a 'telluric star' (TS) — i.e., a star lacking intrinsic features in the scientifically relevant spectral range — close in time and position to the science target. Over a whole night, the corresponding execution time can easily absorb up to 10% of the science time and changing weather conditions might affect the TS spectrum quality, possibly tarnishing the science observation.

Synthetic telluric absorption spectra have recently provided better correction quality than this empirical method, returning the corresponding overhead time back to science. In particular, Molecfit (Smette et al., 2015; Kausch et al., 2015) is being integrated into instrument pipelines, including those of the ELT instruments (Figure 2). The Molecfit_model routine first adjusts molecular abundances and the parameters of the line spread function (LSF), and possibly corrects for inaccurate wavelength calibration by fitting data in small regions of the science spectra representative of the telluric lines. Then the Molecfit_calctrans routine uses this information to calculate the telluric transmission spectrum over the whole spectral range, so that the Molecfit_correct routine can deliver the corrected spectrum.

The quality of the correction depends on the availability of suitable telluric lines for the fitting process, and hence on the characteristics of the science target spectra. Improvements rely on independently determining the fitted parameters. A microwave radiometer pointing at the target coordinates already provides temperature and humidity profiles (Smette, Kerber & Rose, 2020). Soon, abundances for molecules other than water vapour — which vary on timescales of days to weeks — will be retrieved thanks to regular *twilight* observation of telluric stars. Although the shape of the ELT instruments LSF will be well known, the WG also studies less understood issues, such as the impact of not filling the slit and effects due to the adaptive optics (AO) system.

Sky subtraction (coordinators: Rubén Sánchez-Janssen and Elena Valenti)

The majority of ELT science cases require observations in the IR, which is notorious for its high sky background. Airglow emission dominates at wavelengths below ~ 2 mm and thermal emission above that, and they must be removed, often down to a few per cent. This is challenging because the airglow lines remain insufficiently characterised — many faint molecular transitions are not yet catalogued — and their high-

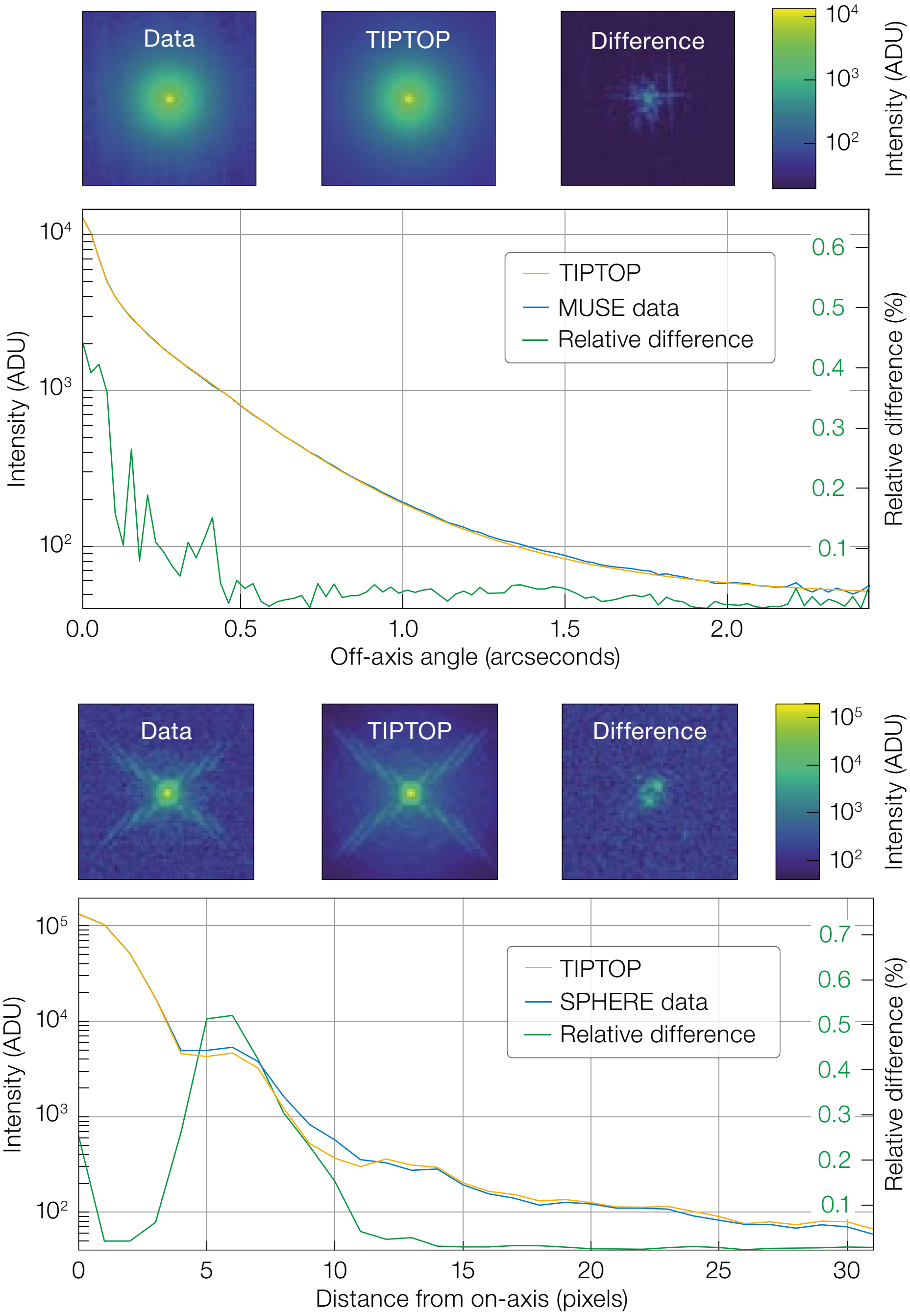

Figure 3. Example of TIPTOP PSF fitting for MUSE-NFM (top) and SPHERE (bottom). TIPTOP is used to fit the actual observations, demonstrating that the model is very accurately reproducing the AO PSFs. In operation, TIPTOP will use parameters estimated by the AO and telescope systems to provide an online PSF estimation.

frequency temporal and spatial variations are poorly constrained. Moreover, we still know very little about the sky continuum emission in the near-IR, except that it is several orders of magnitude brighter than the faint astronomical sources the ELT will be targeting (Oliva et al., 2015).

The Sky subtraction WG addresses these issues with the goal of ensuring that ELT instruments deliver sky subtraction to within a few per cent. To this end, it adopts a two-stage approach:

1. Create a precise empirical model of airglow and continuum emission in the near-IR. We are carrying out a comprehensive screening of faint sky lines through a dedicated VLT/CRIRES programme. Additionally, we have embarked on a study of their temporal and spatial variability with archival VLT/X-shooter and Gran Telescopio Canarias/EMIR spectra.

2. We are working on creating and testing sky-subtraction strategies, combining three distinct methodologies: 1) techniques based on a physical model of the sky emission (Noll et al., 2014); 2) probabilistic algorithms based on the statistical properties of the sky signal (Soto et al., 2016); and 3) optimal on-sky observing strategies (Yang et al., 2013). The first two approaches will benefit from the ongoing development of algorithms to characterise the instrumental LSF (Kakkad et al., 2020).

Spectro-photometric standards (coordinator: Sabine Möhler)

This WG was created to ensure that suitable spectro-photometric standard stars are available by the time the first-light ELT instruments, covering the 0.45 μm to 13 μm wavelength range at various spectral and spatial resolutions, start operating. The spectro-photometric standard stars will be used solely to determine the instrumental response and not for telluric correction (see above). Because the instrumental response is expected to change slowly about 6–10 standard stars per instrument are sufficient, as long as they are evenly distributed in right ascension across the sky and at suitable declinations to avoid observations at large airmass.

For each star reliable reference data must be available across the required wavelength range at the defined brightness intervals. We first investigated whether existing standard star catalogues may be used. It turned out that HARMONI may use the same flux-standard stars as X-shooter and that the standard star catalogues of CRIRES and VISIR are suitable for METIS.

For MICADO, however, new spectrophotometric standard stars need to be defined because the existing ones are too bright. Candidate white dwarf stars have been identified and observed with X-shooter. The analysis is ongoing. The flux-calibrated X-shooter spectra will be fitted with white dwarf model spectra and the best fitting ones will be used as noise-free reference data for the new flux-standard stars.

Guide/AO stars (coordinators: Paolo Padovani and Giacomo Beccari[b])

Crucial to the operation of the ELT is the availability of stars in the field of view, both for the telescope and the instruments, with the necessary astrometric precision and brightness for telescope acquisition, wavefront control, and AO. The telescope will need up to three natural guide stars (NGS), with information on their optical magnitudes (in the *R* band or *G* band) and good astrometric precision. This can be achieved by using the Gaia stellar catalogue[2], which by the time the ELT operates will have reached its end-of-mission final data release, with accurate parallaxes and proper motions. Depending on the AO mode, the instruments may use NGS in the optical (for example, single-conjugate adaptive optics [SCAO]) or near-IR (laser tomography adaptive optics [LTAO] and multi conjugate adaptive optics [MCAO]).

The work performed so far by this WG includes: 1) the exploration of options to estimate *H*-band magnitudes for stars based on their optical colours and Gaia *G*-band magnitude, since all-sky, near-IR catalogues are not presently available; 2) the determination of the fraction of binaries with close separation (≤ 1 arcsecond and similar brightness (within 3 magnitudes), since these are ‘problematic’ as ELT guide stars. We find that ~ 20% of stars that could be selected for wavefront sensing are expected to have a companion that could potentially hamper ELT operations; and 3) the drastic reduction of this contamination by using a convolutional neural network approach. The WG at present can produce a guide-star catalogue around user-specified International Celestial Reference System (ICRS) coordinates based on Gaia EDR3, with near-IR fluxes derived from VISTA and UKIRT surveys, and *J*- and *H*-band predictions based on optical data.

Simulated PSF and AO performance (coordinator: Benoît Neichel)

Since almost all ELT observations will be AO-assisted, the ESO community exposed to AO-corrected data will increase significantly and many future ELT users might not be AO experts. To assist the ESO community in preparing their AO observations, a fast algorithm — called TIPTOP (Neichel et al., 2021) — has been developed, which produces the expected AO PSF for any of the existing AO observing modes (SCAO, LTAO, MCAO, Ground Layer Adaptive Optics [GLAO]) and any atmospheric conditions. Called from a simple application programming interface, TIPTOP is fast enough (a few seconds per PSF) that users can predict the performance of as many configurations as needed, at any sampling, position in the field and wavelength. Moreover, TIPTOP will guide the user to select the best guide star constellation and it will be interfaced with the instrument simulator (see below) to predict the final signal-to-noise ratio (SNR) expected for the target. TIPTOP will also serve for queue scheduling and quality-control, and will provide a first PSF estimation associated with each science observation block. This last step could be seen as a first approach to PSF reconstruction (see below) and may be good enough for some science cases. In preparation for the ELT, TIPTOP will be deployed and tested on various VLT instruments, including ERIS, MUSE, CRIRES, SPHERE, and eventually MAVIS. The WG is currently working towards the fine tuning of the algorithm vs. on-sky observations and first results are very encouraging (Figure 3). TIPTOP has recently been installed as a ‘level3 micro-service’ on a dedicated ESO machine and is available for beta-testing[3]. Readers are encouraged to test TIPTOP and send feedback.

PSF reconstruction (coordinator: Joël Vernet)

All currently foreseen ELT instruments will benefit from at least one flavour of AO correction. Developing tools to estimate the highly complex and varying PSFs produced by these systems is therefore crucial to enabling solid measurements of astrophysical quantities (photometric, astrometric, morphological etc.). This need for reconstructed PSFs is further exacerbated by the limited field of view of the ELT instruments and the lack of suitable isolated point sources to estimate the PSF from the science data.

As a starting point, a WG subgroup focused on establishing the state of the art, putting together an overview of the PSF reconstruction approaches currently being explored by various research groups, estimating their respective performance, their range of applicability, and the input and assumptions they rely on. A comprehensive report led by Olivier Beltramo-Martin and others[4] was produced and is available on the WG wiki page.

The most accurate PSF reconstruction (PSFR) algorithms depend heavily on telemetry data produced by the AO systems, such as wavefront sensor data, measured slopes, control matrices or deformable mirror commands at frame rates reaching hundreds of Hz. While extremely data intensive, these methods hold the best potential for reaching percent-level accuracies and there is a clear consensus among WG members that these most promising approaches should be enabled at the ELT. The strategies for AO telemetry data production proposed by the HARMONI, MICADO, and MORFEO consortia were compared and ways to optimise data rates to stay within the practical archiving limit of 10 TB per night were explored (for example, time averaging, pre-processing, compression). Synergies with the Opticon-RadioNet Pilot Joint-Activity JA3.3.2 for virtual access to AO telemetry and development of data storage and exchange standards are also being discussed.

Further topics the WG will focus on include strategies to calibrate non-common path aberrations and the evaluation of PSFR algorithms on current 8-metre-class AO facilities.

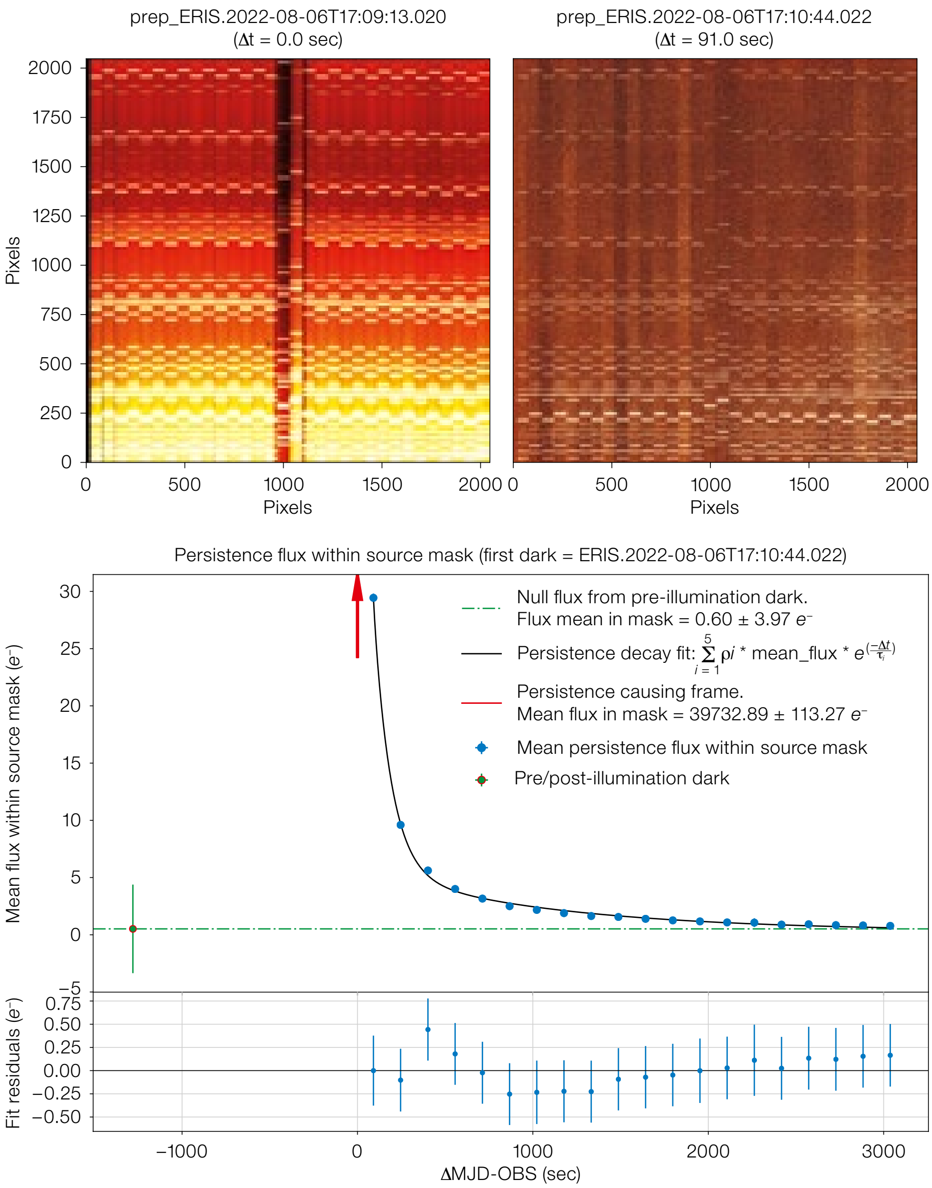

Figure 4. Top Left Panel: An ERIS/SPIFFIER arc lamp calibration, intentionally overexposed to create persistence in a series of dark exposures taken immediately afterwards (peak flux levels are ~ 60 ke⁻).

Top Right Panel: The first 150-second dark following the arc lamp exposure. This dark frame has been dark-corrected by a clean master dark unaffected by persistence. The peak persistence flux levels are ~ 400 e⁻.

Bottom Panel: The exponential decay of the persistence as measured from a series of 20 long darks following the arc lamp exposure. Approximately 2000 seconds after the arc lamp the persistence signal has decayed to zero.

High-contrast imaging (coordinators: Faustine Cantalloube, Markus Kasper, and Christophe Verinaud)

The three first-light instruments for the ELT (HARMONI, METIS and MICADO), and potentially two of the next-generation ones (ANDES and PCS), include a high-contrast imaging (HCI) mode. This mode is a combination of a high-performance AO correction and an advanced coronagraphic technique that suppresses the starlight diffracted by the telescope aperture before it reaches the science camera. A high-contrast image has a high dynamic range (1:10 000), making it extremely sensitive to wavefront residuals. These residuals might come from uncorrected atmospheric turbulence, inherent limitations of the AO and/or coronagraph, the telescope structure or optical aberrations that are not corrected upstream by the AO. Usually, image processing tailored to HCI data is applied to remove most of these residuals and reach a contrast of 1:1 000 000 or higher. This allows, for example, the detection of mature giant gaseous planets orbiting at a few tenths of an au around low-mass stars, and potentially the circumstellar disc in which they form and evolve.

In this context, the goals of the recently established HCI WG are to: 1) share information, tools, and necessary inputs; 2) report the main limitations foreseen and specific requirements needed for the operations at the ELT; and 3) provide a realistic contrast budget to guide future HCI observations. The three main deliverables are: 1) to implement quick HCI simulations into the ELT simulator; 2) to build the exposure time calculator for HCI modes, with the corresponding observing guidelines; and 3) to prepare for the observation and data exploitation by developing diagnosis and performance tools. This work will benefit common calibration strategies, optimal use of metadata, and definition of scheduling constraints. Therefore, this WG is in close relation to the Astro-weather, AO performance and Instrument simulations and exposure time calculator WGs.

Line calibrations (coordinator: Carlos Martins)

This WG stems from the strict requirements on the precision, accuracy and stability of cutting-edge astrophysical tests of fundamental physics. One example is that currently useful transitions for measurements of the fine-structure constant need a laboratory wavelength precision of 20 m s^{-1} or better. For the ELT this becomes 4 m s^{-1}, implying that many of them require improved laboratory measurements. Such improvements are difficult with current techniques: the natural alternative is to use laser frequency combs (LFCs).

In 2021 the WG made recommendations on ANDES calibration strategies (Martins et al., 2021). In summary: 1) ANDES must have a means to verify wavelength calibration stability requirements, including non-common path errors; 2) monitor novel space and drone-based calibration systems for astronomical telescopes; 3) redundancy in ANDES calibration systems is essential — ANDES should include an iodine cell (I_2 cell); 4) one must study whether classical extraction schemes are sufficient for ANDES — delivering precise and accurate uncertainties must be a top-level requirement for the data reduction software; and 5) the wavelength range of any calibrator systems must fully cover the instrument wavelength range.

The WG also recommended that an I_2 cell be installed on ESPRESSO, for a twilight calibration programme observing bright, fast-rotating stars to explore the measurement of non-common path and detector effects, how they can be tracked with time, and how accurately they can be removed. A Use Case Proposal was submitted to ESO in November 2021, and the corresponding Change Request is in progress.

The experiment would have two steps: a commissioning run (for two weeks) and a monitoring campaign (every two weeks for one year and around major events). The Big Questions Institute in Sydney has funded the hardware. The cell procurement and calibration are ongoing, and it will be shipped to Paranal when ready so that the experiment can start, provided the ESPRESSO LFC is operational.

Instrument simulations and exposure time calculator (coordinator: Kieran Leschinski)

The sheer size and complexity of the ELT and its instruments that mandates the use of AO systems in order to observe at the diffraction limit, and the novel science that the ELT will deliver with unprecedented spatial resolution, all require a more advanced instrument simulator to complement the traditional exposure time calculator.

The observation simulator WG has been tasked with creating requirements for a micro-service for the ESO observation preparation environment which can return realistic simulated observations in a timely manner. The working title of this micro-service is ELVIS, the ELT Virtual Instrument Simulator. It will allow users to create 1st-order simulations of their proposed observation, as well as providing SNR estimates in the output format of the chosen observing template. ELVIS will not be created from scratch. The instrument consortia have already invested time and effort into developing instrument data simulators. ELVIS should re-use as much of the existing data and code bases as possible, while taking advantage of the future micro-services developed by other WGs, for example TIPTOP, Pyxel, Skycalc, etc.

Major recent results from the work package include: 1) converging on several key elements of the project scope and its deliverables; 2) the decision to recommend using the ScopeSim generic instrument data simulation ecosystem (Leschinski et al., 2020) as the backbone of the micro-service; 3) definitions of the interfaces with three of the primary external micro-services.

Recent benchmark tests have shown that there should be no major hurdles with implementing the ELVIS micro-service. Readers who do not wish to wait for ELVIS may start experimenting with ELT observations by installing the ScopeSim package in their local python environment.

Detector effects (coordinator: Elizabeth George). PyXel detector simulations (coordinator: Benoît Serra)

These two closely linked WGs deal with detector performance: detector effects and advanced detector simulations. They are complementary and feed into each other.

The goals of the Detector effects WG are two-fold: 1) to gather knowledge from detector engineers, who through testing in the lab can characterise detector effects that may impact the science, for example, non-linear effects (low count rates), electronic cross talk, persistence, noise, glow; and 2) have scientists analyse the impact on their science resulting from various detector effects.

The main deliverable is a list of common detector effects that can be used as inputs into the Instrument simulations WG (see above). Additionally, the WG provides input to detector groups on a detector characterisation plan (based on detector effects that may impact the science) for each instrument, which includes delivery of standard data products for each detector that can be used to quantify various detector effects.

The advanced (Pyxel) detector simulations WG has the main deliverables of creating simulated detector readouts including all of the detector effects that can be used by various instrument simulators to quantify the impact of detector effects on science data and developing pipeline algorithms to account for these effects.

The two WGs have made good progress towards these goals in the last few years, particularly with the H4RG and H2RG detectors that will be used in the three first-light ELT instruments, HARMONI, MICADO, and METIS.

The Detector Group at ESO has developed standardised characterisation procedures and data products for all the relevant detector effects in the H4RG detectors in MOONS, which will be extended and applied to the detectors for the ELT instruments. This characterisation procedure has been submitted as part of the final design review data packs for MICADO and HARMONI.

Within ESO's collaboration with the European Space Agency (ESA), we have been developing the open-source Pyxel[5] detector simulation framework (Arko et al., 2022), which allows full simulation of detectors and the possibility of implementing any model the user desires. Together with the Pyxel developers at ESA, we held a Detector Modelling workshop in June 2021, which brought together a community of detector engineers and scientists to discuss everything from characterising detectors to developing detector simulators (George et al., 2021). Finally, this year Pyxel has been presented at several conferences (SPIE, EIROforum, SDW2022 and next will be the CMOS workshop at ESA) with several demonstrations of its capabilities. It is now possible to create simulated exposures with H2RG or H4RG including a wide variety of important detector effects using Pyxel and to calibrate some of those models using our laboratory test data.

Persistence modelling (coordinator: Mark Neeser)

Persistence is the effect whereby a remnant signal from an exposure is imprinted on subsequent images. This effect has long been known to affect HgCdTe near-IR detectors and, if severe, the persistence artefacts can last from hours to several days, negatively affecting the quality of subsequent observations. An example of persistence, intentionally caused within calibration data obtained during ERIS commissioning, is shown in Figure 4. It is hypothesised that persistence is caused by defects and/or impurities within the HgCdTe strata of near-IR detectors. These defects provide sites where light-induced charges are trapped. These trapped charges are generally not released during the detector read but instead randomly decay during subsequent exposures and thereby mimic newly received photo-charge (Smith et al., 2008; Leisenring et al., 2016; Tulloch et al., 2019).

The goal of the Persistence WG is to develop an algorithm and observing strategy for limiting and correcting persistence effects in science data (see Neeser, 2021 for a detailed description). We intend to obtain a deep understanding of how persistence behaves in each new ESO IR detector. This will be done in the laboratory by the ESO Detector Group following a well-defined series of tests. Specifically, this will provide us with a map of the maximum number of persistence traps available in each pixel, the fraction of incident photons that can be converted to persistence traps, and a table of the time constants used to characterise the detector and the relative contribution that each makes to the distribution of persistence traps. A method has been developed to reliably and automatically create persistence maps that can be used to correct any given science exposure.

Using the characterisation data and parameters for each near-IR detector, a model for persistence is used to track the accumulation and decay of persistence traps affecting any input science exposure. These traps are tracked through a series of exposures taken prior to correction of the science frame and a cumulative persistence map is computed for the science frame. Since the data analysed for persistence can be proprietary, this analysis must be done by the ESO Quality Control Group in Vitacura.

The goal is to compute a persistence map for each science exposure and to ingest it into the ESO archive as an associated calibration frame. Since persistence is a rare event, we expect that most maps will contain no significant persistence signal. A blind correction of each science frame for persistence would, therefore, only add noise to the image. Because of this, the subtraction of a persistence map will have to be left to the user. Refining the strategy for this has been helped by the lessons learned during ERIS/SPIFFIER and ERIS/NIX commissioning.

Acknowledgements

Many thanks to Remco van der Burg who was in charge of the overall coordination of the ELT WGs until February 2022. CJM acknowledges FCT and POCH/FSE (EC) support through Investigador FCT Contract 2021.01214.CEECIND/CP1658/CT0001.

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Links

[1] ELT website: https://elt.eso.org
[2] GAIA catalogue: https://gea.esac.esa.int/archive/
[3] TIPTOP: https://tiptop.readthedocs.io/en/dev/
[4] Subgroup report on PSFR algorithms: https://eso.org/wiki/pub/ELTScience/PSF_reconstruction/ESO_WG_-_PSFR_Algorithms_BeltramoMartin.pdf
[5] Pyxel simulation framework: https://esa.gitlab.io/pyxel/

Notes

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[b] Until February 2022 the Guide/AO stars WG was lead by Remco van der Burg.

The VLT Survey Telescope (VST) at ESO's Paranal Observatory in Chile has captured this richly detailed new image of the Lagoon Nebula. This giant cloud of gas and dust is creating intensely bright young stars, and is home to young stellar clusters. This image is a tiny part of just one of eleven public surveys of the sky now in progress using ESO telescopes. Together these are providing a vast legacy of publicly available data for the global astronomical community.

ESO/VPHAS+ team

The Eta Aquariids meteor shower, which peaked in early May this year, was captured in this stunning image by astrophotographer Petr Horálek. It was taken near San Pedro de Atacama, a Chilean town about 50 km away from the Chajnantor observatory site, where APEX and ALMA, astronomical facilities co-owned by ESO, are located. The Eta Aquariids meteors are caused by leftover debris from Halley's comet and make up the bright, arrow-like darts of light in the photo.

ESO/P. Horalek

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ESO's Role in Advancing the UN Sustainable Development Goals

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Building on decades of work, in 2015 the United Nations Member States adopted the 2030 Agenda for Sustainable Development[1], based around a set of measures formulated to be a guiding plan of action to improve human lives and protect the environment, namely, the Sustainable Development Goals (SDGs[2]). The main aim of the SDG's is to eradicate poverty in all its forms, the achievement of which requires that all countries and stakeholders work together to implement strategies that improve health and education, reduce inequality, address climate change, and spur economic growth. The United Nations General Assembly has proclaimed 2022 as the International Year of Basic Sciences for Sustainable Development, the goal being to highlight the role of basic sciences in supporting sustainable development.

The European Southern Observatory (ESO), with 16 Member States across Europe along with the host and partner state of Chile and with Australia as a strategic partner, supports the achievement of the UN SDGs in their three different dimensions: economy, society, and environment. Through its mission to design, build, and operate world-leading observational facilities that help advance our knowledge about the Universe, as well as to foster international cooperation for astronomy, ESO has a role to play in achieving the goals and targets set by the UN by being a driver of scientific research and supporting education activities at all levels across the world.

ESO contributes to 13 out of the 17 SDGs (highlighted on the graphics below). The goals that ESO contributes to are related to improving quality in education, striving for diversity, equity, and inclusion within educational, science and engineering settings, goals related to technology, innovation, peaceful scientific cooperation, as well as environment and health. In what follows, examples of ESO initiatives and actions that contribute to each development goal are briefly described.

Good Health and Well-being (SDG 3)

ESO contributes to the third SDG, Good Health and Well-being, through its advocacy for preserving the dark night skies and by enabling the development of technology that finds uses outside of astronomy, including in medical applications.

Preserving the darkness of the skies goes beyond astronomical research. There is a wealth of scientific literature studying the impacts on light-polluted skies on human health. For instance, the 2017 Nobel Prize of Medicine or Physiology, was awarded to individuals whose discoveries suggest that the human body clock requires natural daylight rhythms and dark skies to

function properly. Artificial light has been linked to low levels of human melatonin, which might lead to health risks. Moreover, scientific studies suggest that artificial light increases the risk of depression, sleep disorders, obesity, and cancer. Further, the dark night sky is a source of awe, education, outreach and community, with stargazing having the potential to promote health and wellness in society. Stargazing has been shown to offer benefits to human wellbeing by nourishing positive emotions and connectedness with nature. By actively advocating for the protection of the dark sky, ESO, in collaboration with other observatories and the Chilean government, is making its own contribution to healthy lives across the planet[3].

The development of ESO's cutting edge instrumentation involves a wide range of technology development. Through the EU-funded ATTRACT initiative, the German institute innoFSPEC is transferring astronomical technology from the MUSE integral field spectrograph on ESO's Very Large Telescope into cancer diagnostics tools.

Quality Education (SDG 4)

ESO plays a pivotal role in training early-career astronomers, astrophysicists, engineers, and communicators of science from across the world. Training is done through a broad range of programmes and initiatives, such as studentships, fellowships, internships, and summer research programmes. In the last decade, ESO has trained over 260 students in science and engineering from more than 40 countries, over 90 interns in science communication, graphic design, astronomy, engineering, and science policy and diplomacy, and hosted over 150 postdoctoral fellows in astronomy and engineering from more than 30 countries. In Chile specifically, ESO funds post-doctoral programmes in astronomy at Chilean academic institutions and provides studentships at the ESO offices in Santiago for students enrolled in Chilean universities. After participating in these training programmes, these young professionals are equipped with a relevant set of transferable skills, such as in data science, programming, and/or machine learning.

Through the ESO Supernova Planetarium & Visitor Centre, located in Garching, Germany, ESO promotes and increases scientific literacy in society and inspires children and young people to engage in science, technology, engineering, and mathematics (STEM). Since opening in spring 2018, the centre welcomes around 70 000 people each year. The education programme of the ESO Supernova is offered completely free of charge and is available to all compulsory stages of education, from kindergarten through to the end of secondary education. Over 9000 of the annual visitors are school pupils and their teachers, typically coming from more than seven different countries each year, who engage with at least part of the education programme. A further 350 teachers and educators are engaged annually in professional development activities.

ESO also supports other organisations in their astronomy education endeavours by providing open-source materials, enabling facilities around the world to share the fascination of astronomy with as varied an audience as possible.

Furthermore, ESO also promotes quality education by making the data from observations conducted with its telescopes public. The petabyte-sized ESO Science Archive contains open data from all ESO telescopes, which can be used for research, education or outreach purposes. ESO also has an extensive database of images and videos for outreach purposes. By making these materials available for free, ESO ensures that audiences everywhere can experience the wonders of the cosmos.

Closing the Gender and Inequality Gap (SDGs 5 and 10)

ESO is committed to equity, diversity and inclusion[4] and believes that astronomical education and research can be a tool to empower and inspire women around the world and bring people of different backgrounds together in collaborations.

The ESO Diversity & Inclusion Committee advises ESO's management on goals, policies and good practices pertaining to all aspects of diversity. ESO is a member of the GENERA Network (Gender Equality Network in Physics in the European Research Area), fostering global collaboration over gender equality policy in physics between research organisations, associations, and consortia.

A memorandum of understanding between ESO and UN Women was signed in 2020 with the goal of assessing the gender gap in STEM careers, focusing on creating training opportunities for women, particularly in the Antofagasta region in Chile. Antofagasta is the closest hub to ESO's Paranal Observatory, and the city hosts ESO support offices. Under the framework of this agreement, ESO has participated in the Second Chance Programme (Tu Oportunidad) by training a group of women at Paranal Observatory in key astronomical technology skills, such as coating large telescope mirrors, allowing them to expand their job opportunities. In addition, members of ESO staff take part in LIQCAU: + Mujeres en Ingeniería, a mentoring project led by the Universities of Antofagasta.

Economy, Technology and Innovation (SDGs 8 and 9)

ESO invests in engineering, science, and innovation to design and build advanced telescopes and state-of-the-art instrumentation by developing new technologies such as astronomy technology in optics, engineering and intercontinental data transfer, medicine and imaging, sensor and detector technology. In this way ESO generates new markets, job opportunities, and industrial collaborations, and is contributing economically to society. As presented in the dedicated report ESO's Benefits to Society[5], ESO's economic impact can take several different forms: from direct industrial return to suppliers, economic and innovation effects, to improved expertise and the creation of new jobs and multiplier effects in individual countries. For instance, over 80% of the € 1.3 billion development construction budget for ESO's upcoming Extremely Large Telescope (ESO's ELT) is being invested in contracts with industry. These contracts are primarily distributed across ESO's Member States, providing significant industrial return to these countries, creating new jobs and promoting the emergence of new technologies and expertise.

Adaptive optics systems, necessary to correct the blurring that Earth's atmosphere causes, rely on fast and low-noise sensors, as well as on powerful lasers. ESO initiated collaborations between industry and academic groups which have led to the development of two different detector technologies working in different wavelength regions. ESO has played a central role in these developments, both of which have resulted in technology transfer to industry, subsequently resulting in commercial products that are used in a variety of other research fields. ESO, together with its industry partners, has worked to develop compact powerful lasers, which are currently in operation on ESO's Very Large Telescope (VLT) and will be used on the ELT in the future. This has been the first transfer of patented technology from ESO to industry. In addition to their application in astronomy, the high-powered lasers have uses in the fields of space situational awareness and optical satellite communications, which open up opportunities for further markets for the technology.

Climate, Environment, Sustainability, Clean Energy and Life on Earth (SDGs 7, 11, 12, 13, and 15)

Environmental awareness and sustainability are core values for ESO and the organisation is developing and implementing a comprehensive environmental strategy in order to reduce its carbon footprint and the environmental impacts of its operations[6]. ESO's work, while providing astronomers worldwide with the best tools to enable key scientific discoveries and benefiting society in many ways, places significant demands on the environment and resources. Thus, ESO strives to reduce its carbon footprint and environmental impact.

One of the key ways in which ESO is mitigating its impact on the environment is by running its observatory sites on renewable energy. The observing facilities at ESO's La Silla and Paranal sites in Chile are powered by clean, renewable energy coming from photovoltaic plants built near the observatories. The goal is to have 100% of operations at the sites supplied by these power plants. All the renewable energy not used for scientific operations is injected into the Chilean energy grid. In future, the Paranal photovoltaic power plant will also supply energy to ESO's ELT.

ESO is committed to reducing the environmental damage of long-distance travel by making extensive use of video-conferencing facilities, saving up to 800 tonnes of CO_2 equivalent per year. On site, ESO is gradually replacing its fleet of vehicles with electric cars and aims to use no fossil fuels across all ESO's sites.

The facilities that make up ESO's Garching headquarters extension office buildings and a technical building, inaugurated in 2013, have significantly lower energy consumption than typical for buildings of similar size. This is due to the well-insulated façade and the fact that the office building is heated and cooled through concrete core activation: groundwater is used together with a heat pump and supplied with district heating using geothermally heated water. Green measures have also been incorporated into the design of the ESO Supernova Planetarium & Visitor Centre. The facility received the DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen or German Sustainable Building Council) Gold certification for sustainability with respect to its green economical, socio-cultural, technical, and ecological aspects.

Another way in which ESO contributes to an environmentally sustainable planet is through its initiatives to preserve the dark night skies. For example, there is substantial evidence that lit night skies have a negative impact on wildlife or contribute to increasing a region's climate footprint.

ESO as a model for peaceful scientific cooperation (SDGs 16 and 17)

ESO is a model for peaceful scientific cooperation by promoting international political and cultural understanding between society, science, and technology for the benefit of humankind. The organisation is well suited to this role as collaboration has been part of the organisational culture of ESO since its foundation in the 1960s, and international partnerships penetrate every aspect of its operations. It encourages countries to work together to create a scientific, technological, and policy capacity for development that is beyond the reach of each of its Member States alone.

Given ESO's position as a centre of gravity for astronomy in Europe, ESO is firmly embedded in, and has an impact on, European science policy. ESO is a founding member of the European Intergovernmental Research Organisations forum (EIROForum) that brings together eight of Europe's largest research organisations with extensive expertise in the areas of basic research and the management of large, international infrastructures, facilities, and research programmes. The mission of EIROForum is to combine the resources, facilities and expertise of its member organisations to support European science in reaching its full potential, both in their technical and scientific areas, as well as in diversity, equity, and inclusion-related issues and challenges.

Furthermore, ESO has a permanent seat on the UN's Committee on the Peaceful Uses of Outer Space and has made key policy contributions to the assessment of the impact of satellite megaconstellations, safeguarding the dark sky, and protecting Earth from asteroids. As for the last of those, ESO is a member of the UN-mandated International Asteroid Warning Network, which is a global collaboration that monitors the skies for potentially threatening asteroids.
ESO is also one of the vectors of scientific cooperation between Europe and Latin America. The construction of new observatories in Chile generates an ideal scenario for exchange between Chilean, Latin American, and international scientific communities. The creation of ESO's regional relations office at the end of 2019 is a clear sign of ESO's commitment to strengthening its presence and dialogue with Chilean communities.

Concluding remarks

The UN SDGs provide a useful high-level guide to understanding and communicating how ESO contributes to an agenda broader than its defined mission. ESO can now communicate these successes to its stakeholders and ensure that the basic principles of the UN SDGs and the values they espouse are intrinsic to ESO's own defined values. This is more than communication and PR, however. While the organisation cannot deviate from its mandated mission, the framework of the UN SDGs helps to ensure that each step taken to deliver world-leading astronomy facilities is seen through a sustainability governance lens. ESO's operations are gradually being infused with more sustainable practices.

Links

[1] UN 2030 Agenda for Sustainable Development: https://sdgs.un.org/2030agenda
[2] UN Sustainable Development Goals: https://sdgs.un.org/goals
[3] Dark and quiet skies preservation at ESO: https://www.eso.org/public/about-eso/dark-skies-preservation/
[4] Diversity, Equity, and Inclusion at ESO: https://www.eso.org/public/about-eso/sustainability/dei-at-eso/
[5] ESO's Benefits to Society report: https://www.eso.org/public/products/brochures/brochure_0076/
[6] Environmental sustainability at ESO: https://www.eso.org/public/about-eso/green/

Three-colour composite mosaic image of the Eagle Nebula (Messier 16, or NGC 6611), based on images obtained with the Wide-Field Imager camera on the MPG/ESO 2.2-metre telescope at the La Silla Observatory. At the centre, the so-called "Pillars of Creation" can be seen. This wide-field image shows not only the central pillars, but also several others in the same star-forming region, as well as a huge number of stars in front of, in, or behind the Eagle Nebula. The cluster of bright stars to the upper right is NGC 6611, home to the massive and hot stars that illuminate the pillars. The "Spire" — another large pillar — is in the middle left of the image.

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Report on the EAS Symposium

ESO@60: A stairway to the Universe

A Symposium to celebrate ESO's 60th anniversary, held at EAS2022 in Valencia, Spain on 30 June–1 July 2022

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The symposium ESO@60: a stairway to the Universe was held during the European Astronomical Society (EAS) annual meeting in Valencia, Spain, in June 2022. The focus of the symposium was on the scientific achievements with ESO facilities over the last 60 years. The programme consisted of six sessions of 1.5 hours each. Each session covered a broad theme: Extrasolar Planets, Astrochemistry and Nucleosynthesis, Stellar Populations and Star Formation, Black Holes, Cosmology and Galaxy Evolution, and a Look Ahead to ESO's Extremeley Large Telescope and the next decade. Eight keynote speakers introduced their topics by highlighting how the ESO facilities and their operations, including the end-to-end dataflow system and the ESO Science Archive Facility, contributed to the scientific advancements in their specific areas. The current and two former ESO Director Generals, namely Xavier Barcons, Catherine Cesarsky and Harry van der Laan, attended the symposium and participated in the lively discussions.

From an idea by visionary European astronomers in the 1950s, and the signing of the ESO Convention on 5 October 1962[a], today ESO is the world's most productive ground-based observatory, with over 19 000 refereed publications based on data acquired with its facilities. ESO operates the La Silla Paranal Observatory, hosting some of the world's largest and most advanced observational facilities at three sites in Northern Chile: La Silla, Paranal and Chajnantor[b]. Furthermore, these ESO facilities have contributed to major scientific discoveries, such as the accelerated expansion of the Universe, the existence of black holes, the detection and characterisation of exoplanets, the formation and evolution of stars and planets, and the history of galaxies. Realising the vision of its founders, ESO has fostered and supported the ingenuity and scientific creativity of the scientists in its Member States. The scientific organising committee (SOC) of the ESO@60: a stairway to the Universe symposium was composed of ESO astronomers and Council members. The SOC members were the current ESO Director General Xavier Barcons (ESO), ESO Council President Linda Tacconi (Max Planck Institute for Extraterrestrial Physics, Garching, Germany), Amina Helmi (Kapteyn Astronomical Institute, Groningen, the Netherlands), Rob Ivison (ESO), Antoine Mérand (ESO), Michele Cirasuolo (ESO), Paola Andreani (ESO), and Francisca Kemper (ESO) and it was co-chaired by Magda Arnaboldi, Carlos De Breuck and Bruno Leibundgut, all from ESO.

The symposium programme[1] consisted of six sessions, each covering a broad theme: Extrasolar Planets, Astrochemistry and Nucleosynthesis, Stellar Populations and Star Formation, Black Holes, Cosmology and Galaxy Evolution, and a Look Ahead to ESO's Extremeley Large Telescope and the next decade. Following a keynote introductory talk, each session then led on to the scientific highlights in cutting-edge research being pursued by exciting and challenging ongoing observing programmes. Presentations featured contributions from the PIs on the scientific achievements of the ESO public surveys, both imaging with the Visible and Infrared Survey Telescope for Astronomy (VISTA) and the Very Large Telescope (VLT) Survey Telescope (VST), and spectroscopic. These were complemented by contributions from community members who had accessed the published public survey science data products via the ESO archive for their own independent science. From the scientific achievements with ESO facilities over the last 60 years, the programme moved on to a forward look at the next technological challenges and discoveries. The discussion of future endeavours included the next big eye on the sky, ESO's Extremely Large Telescope (ELT) with its 39-meter-diameter mirror, its operations and dataflow, and its synergies with other facilities, including those at ESO, such as the Atacama Large Millimeter/submillimeter Array (ALMA) and, in the near future, the Cherenkov Telescope Array (CTA), and worldwide, such as the JWST, Euclid and Vera C. Rubin Observatory.

The first session of the symposium was on the subject of stellar populations and star formation. The first talks illustrated the results from some ESO public surveys: the Gaia-ESO survey (spectroscopic; PIs Gilmore & Randich) and the VISTA Variables in the Via Lactea surveys (VVV and VVVX) (VISTA imaging; PIs Minniti & Lucas) which are dedicated to the exploration of the physical properties of the Milky Way galaxy components and the inner 3D structure of the Milky Way, including the Galactic bulge, bar and halo. These talks highlighted the scientific results on the metallicity gradients in the Milky Way disc and the peanut-bulge structure of the inner bar and bulge in the Milky Way, including the constraint on the angular speed of the bar from the VVV proper motions. The presentation about the VPHAS+ survey (PI Drew), including the narrow-band Hα imaging, presented improved calibrations and stunning images of the ionised gas and planetary nebulae in the disc of the Milky Way. These contributions emphasised the very important synergies with the Gaia mission and benefits of combining ground-based data with the extended Gaia DR3 data release (published in the middle of June). Both ground- and space-based facilities are working together to provide a new updated cartography of the Milky Way. Contributed talks by Angela Bragaglia, Eleonora Fiorellino, Gabriella Zsidi and Agnes Kospal focused on specific Milky Way objects and star formation tracers in the Milky Way, based on new observations in the optical and near-infrared (NIR) and with ALMA, together with archival data.

The second session turned to astrochemistry and nucleosynthesis. The keynote speaker, Paola Caselli, presented the latest developments in this area, which span from the biochemistry in the pre-stellar cores to extrasolar planets and life. Caselli presented the evidence for complex molecules in the densest molecular clouds in the Milky Way interstellar medium, where the first stages of star and planet formation take place, how the two are intimately related and how dust grains covered with ice are effective transporters of highly complex molecular species. Very important was the illustration of near-infrared spectroscopy, with ISAAC, and also high resolution, with

CRIRES, along with the synergies with ALMA, both spectra and imaging, illustrated by the inspiring image of the protoplanetary disc of HL Tauri[2]. Caselli also set the stage for optical interferometry as a new observing technique to help in the quest to discover and identify rocky planets in the habitable zone around nearby stars. The keynote talk was followed by a presentation by Nic Cox on the ESO Diffuse Interstellar Bands Large Exploration Survey (EDIBLES).

In the cosmology and galaxy evolution session, Françoise Combes, winner of the 2021 L'Oréal women for science international prize, presented the properties and evolution of the star formation and baryonic cycle. Her talk covered the interplay of gas and stars in galaxies as a function of redshift, the extended gas distribution around galaxies, cooling flows and the morphological transformations triggered by hot gas in high density environments. Combes illustrated the advances made possible by the use of VLT instruments working in the optical (MUSE) and the NIR (KMOS, SINFONI, and NACO) along with Hubble Space Telescope imaging and ALMA to map and resolve the inflow, outflow and kinematics of ionised gas in high-redshift objects. The synthesis of these multi-wavelength (from optical/UV to submillimetre and millimetre wavelengths) and multi-spatial-resolution observations showed that the molecular gas fraction was much higher in the past, and that galaxies were baryon-dominated. The circumgalactic medium around galaxies at distances larger than 30–50 kpc is now detected in emission lines, for example Lyα, (CI) and CO, which are excited by starbursts and active galactic nuclei, mostly by outflows. Cooling flows and wakes are seen in X-rays in cluster cores when the brightest cluster galaxy is in motion with respect to the barycenter of these large-scale structures, and molecules form in the filaments. Finally, mapping of CO molecular submillimetre emission showed the formation of molecular filaments along with Hα emission via tides and ram-pressure from galaxies in clusters. This keynote talk set the stage for a vibrant overview of the ESO public extragalactic surveys and Large

Figure 1. Visual summary of the world-leading facilities in which ESO participates or which will be operated by ESO.

Programmes that aim at constraining the time evolution of galaxies and their complex morphologies. The contributions in this session included a presentation on the Large and Small Magellanic Clouds from the VISTA Magellanic Clouds (VMC) public survey (PI Cioni), the extended photometry of galaxies in the nearby Universe (VEGAS project, PI Iodice) and the study of barred galaxies (TIMER project, PI Gadotti). The wide-area survey SHARKS (PI Dannerbauer) in the NIR and the VST ATLAS survey (PI Shanks) in the optical are aiming to study the evolution of galaxies and the baryonic acoustic oscillations: indeed, they are carrying out preparatory work that will support the efforts by the international community with both the Euclid mission and the Legacy Survey of Space and Time.

On the spectroscopic side, including both integral-field and multi-object spectrographs, there were contributions by Francesco Belfiore and Annie Hughes from the PHANGS Large Programme (PI Schinnerer) on MUSE and ALMA on the physical properties of discs, and the LEGA-C (PI van der Wel) spectroscopic public survey which is aimed at studying the kinematics of passive galaxies at redshifts 0.6–1.0. The lively discussion was supported by the presentations from PIs and Co-Is and also from active members of the community (talks by Sara Mascia, Michele Morescu and Nicola Borghi) that made use of the publicly available survey data for their independent research. Dialogue between survey teams and community members generated a constructive exchange of views and results. Such lively discussion was a testimony to the legacy value and the success of the ESO science policies to manage public surveys on behalf of the community.

The other two scientific topics covered in the symposium were extrasolar planets, and black holes in galaxies and their roles as seeds for galaxy formation. The extrasolar planets topic was introduced by Didier Queloz, Nobel Prize laureate in 2019. The search for, and observational results on, extrasolar planets feature prominently in ESO's top ten discoveries. This list includes, among other things, the discovery of a rocky planet in the habitable zone around Proxima Cen, the ALMA image of HL Tauri[2], and the direct measurements of exoplanet spectra and their atmospheres. Queloz built a narrative around the early phases of this quest, which began with measuring Doppler shifts of nearby stars, leading on to more sophisticated observational techniques which culminated in the images from the GRAVITY instrument on the VLT that show a planet orbiting around a bright star at a distance of about 20 au. This research has produced ground-breaking results by utilising networks of telescopes, from the small, to observe planet transits and identify candidates, to 4-metre telescopes, to make radial velocity measurements, all the way up to the 8-metre VLT to carry out interferometry, high-precision and very-high-resolution spectroscopy with ESPRESSO, leading to the detection of rocky planets and their atmospheres. This field of research also makes use of synergies between space observations (with Corot, Kepler, NASA's Transiting Exoplanet Survey Satellite [TESS] and in future with the ESA space mission PLAnetary Transits and Oscillations of stars [PLATO]) and ground-based data (with ESO's La Silla Paranal Observatory and ALMA). The next milestone, the image of the faint blue dot around another star, is one of the science drivers for the ELT. The keynote talk was followed by a contribution from Basmah Riaz on accretion onto, and outflow from, proto-brown-dwarfs.

Violette Impellizzeri gave the keynote talk on black holes in galaxies and their roles as seeds for galaxy formation. Supermassive black holes play a dual role in galaxy evolution, responsible for feedback that can be either negative or positive. Their outflows are believed to be one mechanism that quenches star formation effectively in giant/active galaxies at the cores of clusters, while at the same time triggering star formation under different conditions. Observations in the optical and NIR have been crucial to unmasking the engine powering the active galactic nucleus hidden behind a torus of dust at the centre of most galaxies. Impellizzeri shared the impressive images of the black hole shadows obtained with the Event Horizon Telescope (EHT). Both ALMA and the Atacama Pathfinder EXperiment (APEX) contributed to the VLBI interferometric observations of the radio emissions from the inner regions of the accretion discs around the black hole at the centre of M87 in the Virgo cluster and that around Sgr A*. The ALMA data in the centre of the Milky Way have been a game changer, increasing the sensitivity to the level needed to be able to image the black hole shadow. The EHT images produced for the supermassive black holes in M87 and the Milky Way dominated the attention of the astronomical community, as well as the wider public, following the release of these images during press conferences at the European Commission in Brussels on 10 April 2019[3] and at ESO on 12 May 2022[4]. Impellizzeri concluded her talk by stating that we are now able to detect gas, jets and molecular outflows around supermassive black holes on large angular scales, and the next challenge is to trace the physical links between the two. Also in this session, Nial Tanvir, PI of the VISTA public survey VINROUGE, explored the connection between merging binary neutron stars and black holes, their relation to gravitational waves and the electromagnetic echos of kilonovae.

The session entitled 'Looking ahead: the next decade' began with a keynote talk by Joe Liske. In his extensive overview of the developments at ESO, Liske touched upon the strategy of the organisation for the 2020s and the science priorities, before moving on to the construction of the ELT and the instrumentation plan. He presented a summary of the La Silla Paranal instrumentation with the VLT instrumentation road maps.

Liske began by illustrating ESO's organisational strengths — world-leading facilities, the ability to support a wide set of science cases, its status as an international & intergovernmental organisation (hence stability, including funding), a successful instrument building model and a reliable platform for hosting national/institution facility-visitor instruments. He then described the efficient operations model and the collaboration with the community over the advanced data products, including those coming from the public surveys. Key aspects of ESO are the highly skilled workforce and the student and fellowship programmes, which function as "a convective zone between ESO and its scientific community" (to quote from the presentation). In his talk, Liske drew on the

ESO Strategy for the 2020s (Waelkens et al., 2021). The science priorities for the La Silla Paranal Observatories (operations and instrumentation) lead towards the ELT. A huge amount of construction activity, both in Europe and on site, is contributing to realising the world’s largest optical-IR telescope, with its 39-meter main mirror. First light is planned for 2027 according to the current management projection. The instrumentation plan for the ELT includes MICADO with the adaptive optics module MORFEO, HARMONI with LTAO and METIS at first light. MICADO is a NIR wide-field MCAO imager (PI R. Davies) and HARMONI is the optical and NIR AO-assisted IFU (PI N. Thatte). METIS adds a mid-infrared imaging and spectroscopy capability. To guide the operation of this incredibly complex machine and its instrumentation, working groups are now in place that bring together expertise from the community, instrument consortia and ESO. On the La Silla Paranal Observatory instrumentation, the current count, including near-future instruments, is 16. With the focus on the unique strengths of the VLT Interferometer (VLTI), the coming years will witness the commissioning/construction of ERIS, MOONS and 4MOST on Paranal, and NIRPS and SoXS on La Silla. Liske ended his presentation with a look at the current challenges, including the international environment crisis, but then also asking the question whether the VLT model (instrument building, time allocation, operations etc.) scales well to the ELT. Finally the integration of CTA-South and the next big project… clearly food for thought and plans.

Joe Liske’s talk was followed by contributions from Michael Sterzik and Martino Romaniello, on the operations and the dataflow at ESO. Their emphasis was on how the integrated operation model and data flow will be able to scale to the ELT. See Figure 1 for a visual summary of the world-leading facilities in which ESO participates or that are operated by ESO. On the topic of data management, the new developments at ESO, from quality control, pipeline processing to the generation of science data products, were presented by Martino Romaniello, along with the increased legacy content of the ESO science archive facility. In short, a big push from the raw data to science.

The talk by Guy Perrin illustrated the amazing prospect of optical interferometry with the VLTI and both the impact and opportunity of GRAVITY, not only in respect of observations of Sgr A* but also other science cases, including the ‘live’ observation of extrasolar planets. Roberta Zanin, project scientist for the CTA Observatory, introduced very-high-energy gamma-ray astronomy with the imaging atmospheric Cherenkov technique. The CTA array utilises three different telescope designs to cover a large energy range of gamma rays from

20 to 100 GeV. The CTA telescope time allocation will be driven by standard proposals, and long and large proposals (including Key Science Projects), which will be evaluated on scientific merit. The CTA Observatory is integrated in the ESO programme with 10% of the time on CTA, North and South, available to the ESO community. This creates an exciting opportunity for the multi-messenger/multi-wavelength era.

The concluding remarks of the looking ahead session made it clear that ESO is an organisation that operates world-leading facilities at the La Silla Paranal Observatory and ALMA (together with its international partners) and will do so in the future with ESO's ELT and CTA-South, which calls for the best ESO ever. There are exciting prospects for synergies with space missions, including the JWST, Euclid, Gaia and planet-hunting missions (PLATO, ARIEL) so the future is bright, and we look forward to ESO's next 60 years.

Demographics

The Symposium S14@EAS2022 achieved a good gender balance in both SOC members and keynote speakers with 45% and 50% of females, respectively.

Acknowledgements

We acknowledge the EAS2022 LOC and SOC for the logistics and support during the conference.

References

Waelkens, C. et al. 2021, The Messenger, 183, 3

Links

[1] Symposium programme: https://eas.unige.ch/EAS2022/session.jsp?id=S14
[2] ESO Press Release on HL Tauri: https://www.eso.org/public/news/eso1436/
[3] ESO Press Release on M87 black hole: https://www.eso.org/public/news/eso1907/
[4] ESO Press Release on SgrA black hole: https://www.eso.org/public/news/eso2208-eht-mw/

Notes

[a] On 5 October 1962 a Convention was signed in Paris between Belgium, France, Germany, the Netherlands and Sweden to establish the European Organisation for Astronomical Research in the Southern Hemisphere (ESO). Subsequently, Denmark (1967), Switzerland and Italy (1982) joined the organisation. The number of Member States has increased since then, and now sixteen states are full Member States of ESO.

[b] The Very Large Telescope at Cerro Paranal is ESO's premier site for observations in visible and infrared light. All four unit telescopes of 8.2 metres diameter are in operation with a large collection of instruments. On La Silla, ESO operates two major telescopes (the 3.6-metre telescope and the New Technology Telescope. They are equipped with state-of-the-art instruments built either by ESO or by external consortia with substantial contributions from ESO. ALMA is a partnership of ESO (representing its Member States), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile.

This picture of the nearby galaxy NGC 6744 was taken with the Wide Field Imager on the MPG/ESO 2.2-metre telescope at La Silla. The large spiral galaxy is similar to the Milky Way, making this image look like a picture postcard of our own galaxy sent from extragalactic space. The picture was created from exposures taken through four different filters that passed blue, yellow-green, and red light, and the glow coming from hydrogen gas. These are shown in this picture as blue, green, orange and red, respectively.

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Report on the Workshop

Joint Observatories Kavli Science Forum

held at ESO Vitacura, Santiago, Chile, 25–29 April 2022

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Itziar de Gregorio-Monsalvo[1]
Leopoldo Infante[2]
Elizabeth Humphreys[3]
John Blakeslee[4]

[1] ESO
[2] Las Campanas Observatory, Chile
[3] Joint ALMA Observatory, Chile
[4] NOIRLab, USA

The Joint Observatories Kavli Science Forum in Chile was organised in hybrid mode with the aim of encouraging collaborations, not only with the Chilean institutions, but also between the different observing facilities based in Chile. The meeting featured scientific talks showing results obtained with the astronomical facilities based in Chile, but significant time was also dedicated to round-table discussions on Life Balance, Diversity-Equity-Inclusion, and the Road Ahead (i.e., the future of those Chile-based facilities).

Chile-based observatories have been leading scientific research in several astronomical areas. The forum was organised around the highest-impact scientific results provided by those facilities over the last few years. The aim was to show how these different observatories have contributed to those advances in astrophysics and, with that goal in mind, the organising committee placed particular emphasis on the scientific involvement of the astronomers working at those observatories to achieve cutting-edge results. The intention was to organise a meeting to gather together both observatory staff (astronomers, scientists, fellows, students, engineers, operators etc.) and Chilean institute researchers (postdocs, students etc.) to present their research. This would also reinforce the scientific collaboration between observatories and Chilean research institutes, to examine common experiences and concerns, and to discuss different points of view on how to cope with similar challenges.

Each half-day of the meeting was dedicated to a specific field of astronomy that had seen major advances thanks to the observing facilities based in Chile, followed by dedicated time for discussion.

After an introductory speech that included a report from the Director of the Chilean Astronomical Society (SOCHIAS), Monday was dedicated to the transient sky with talks focusing on cataclysmic variables, multi-messenger follow-up, and supernovae. It was reported that new observing systems are being developed, focused on the management of time-domain observations. We would like to highlight the sharing of the different points of view, concerns and strategies between several observatories during this session. Representatives of all the observatories agreed that although there will be an enormous number of alerts/triggers at the beginning of the Legacy Survey of Space and Time, the rate of triggering will slow down and the tools will adapt, as will the observatories and the community.

Tuesday morning's talks focused on exoplanets and star formation. A great example was presented of successful ALMA+VLT science and how a Chilean-led research team is making great use of all the Chile-based facilities. During the afternoon we had our first round-table discussion, on Life Balance, chaired by Itziar de Gregorio-Monsalvo and with several invited panellists (see de Gregorio-Monsalvo, Hibon & Alcalde Pampliega on p. 44 of this issue for more details). The three key words in the discussion were flexibility, tolerance and empathy, and the conclusion can be summarised as: "Don't live to work but work to live!". Participants spontaneously rearranged the chairs to form a big circle so as to facilitate discussion and be able to see everyone, an arrangement that was then reproduced for each round table.

Wednesday morning's talks targeted the cosmic distance scale and stellar populations. Again we saw great scientific results thanks to the synergy between different organisations and facilities. The afternoon was dedicated to a round-table discussion on Diversity-Equity-Inclusion, chaired by Belén Alcalde and with several panellists (see Alcalde Pampliega, Hibon & de Gregorio Monsalvo on p. 46 of this issue for more details). Everyone showed genuine concern for this topic and agreed it should not be a side-issue. We must educate ourselves in this area to ensure progress.

Thursday's presentations concentrated on extragalactic astronomy: the high-redshift Universe, active galactic nuclei, and large-scale structure. We learned about impressive results from programmes at many different observatories, including some Large Programmes, and the power of combining ALMA and other observations (ground- or space-based) for making progress on important problems in

Figure 1. Round table photo. This room configuration optimised the discussions.

the area galaxy formation and evolution. Through these efforts, the high-redshift Universe is revealing itself more and more.

On Friday morning the talks were centred on technical developments and some issues that we all face at observatories, including the latest astronomical technologies developed in Chile (Polymer Reinforced Carbon Fiber mirrors, adaptive optics) and the impact of low-Earth-orbit satellites on nighttime observations. The afternoon was dedicated to a round-table discussion, chaired by Franz Bauer, with the directors of the Chile-based observatories: Andreas Kaufer (ESO-LPO Director), Leopoldo Infante (LCO Director), Elizabeth Humphreys (ALMA Head of Science Operations), Robert Blum (Director for Operations at Vera C. Rubin Observatory), and the chair of the Chilean Telescope Allocation Committee, Patricio Rojo. Discussions were focused on the road ahead. Panellists and participants engaged in lively discussion of the new projects, observatory sustainability, remote working and the several opportunities to link the different observatories and the Chilean institutes. We all agreed on the efforts and actions that needed to be undertaken to involve the Chilean community and to retain minorities.

Although the weather during the week was highly variable, the quality of the food at each coffee break and lunch, provided by new catering companies that are all managed by Chilean women, spoiled us. The feedback from speakers, panellists, and participants was extremely positive and most of the audience asked for a repeat of the forum. This will allow continued discussion of the progress made, not only from the scientific perspective, but especially on the topics from the different round tables. Everyone left the meeting with a big smile.

Demographics

As with many workshops, the Science Organising Committee sought fair representation from the community. To this end, we voted on 16 invited speakers, using the sole criterion of who would give the best review of each topic. The end result was a 50:50 ratio of male to female invited speakers, with four PhD students delivering invited talks. The Diversity panel had a 50:50 ratio of male to female panellists, The Life Balance panel had a 20:80 ratio of male to female panellists, and The Road Ahead panel an 80:20 ratio of male to female panellists. This last does reflect the actual ratio of males to females in observatory senior management. Attendees came from all Chile-based astronomical observatories and institutions with the following percentages:
– 58% from observatories (ESO, ALMA, NOIRLab, LCO, Carnegie, GMT);
– 42% from Chilean astronomical universities/institutions.

Figure 2. Conference photo.

Of the abstract submissions, 35% were from women, which matched the 35 % of talk allocations to women. The talk selection was made blind (the SOC chair removed first names and identifying information about the authors), so we conclude that the method likely worked to address gender biases. We also had a decent level of participation from young researchers, within the following breakdown according to seniority: ~ 14% students, ~ 18% postdoctoral researchers, 15% engineers and operators, and 48% tenure-track or tenured astronomers and 5% outreach or HR professionals. Each of these groups was well represented in the talks, including the invited talks.

The workshop had a high level of participation, with approximately 110 participants. We attribute this to both the compelling nature of the subject matter, which draws researchers at all career stages, and to the generous support that ensured attendance was completely free.

Acknowledgements

We would like to acknowledge and sincerely thank Christopher Martin and the Kavli Foundation who provided the funding for this forum and without whom this meeting would not have been possible. We also would like to acknowledge the forum proposal Co-Is, the SOC, the LOC and the ESO logistics team. We also would like to thank the ESO Chile Office for Science and Logistics for their support with the organisation of this forum.

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Work-Life Balance Round-Table Discussion at the Joint Observatories Kavli Science Forum

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One of the main goals of the Joint Observatories Kavli Science Forum held at ESO Vitacura in April 2022 was to bring to light common problems shared by personnel working at Chile-based observatories and universities. The difficulty of balancing a highly demanding work regime and personal life was identified as a common challenge faced by people working in astronomy-related environments, as discussed in a round table on work-life balance. No matter whether you work at an observatory or in academia, trying to maintain a reasonable balance between personal life and work is a difficult task, as a result of working shifts at the observatories, travel to national or international conferences, teaching duties, the continuous exposure to tight deadlines, or a combination of all of these. Remote working in the worst times of the pandemic made this balance even more difficult, and after the peak of the pandemic many people suffered burnout and exhaustion. A three-hour round table divided into two sessions was organised on 26 April 2022 to share and discuss the main issues that affect a healthy work-life balance in astronomy. This forum provided a good environment for discussion of how to improve this situation, in preparation for once the pandemic is under control.

A panel composed of a diverse group of astronomers at different career stages, of different genders, and working in different environments was convened to propose a set of topics for discussion by the participants at the meeting. Specifically, the panel consisted of: professor at the University of Valparaiso and former ESO Chile Fellow Yara Jaffe; telescope operator and technical assistant at Las Campanas Observatory, deeply involved in outreach inclusive initiatives, Carla Fuentes; ESO Fellow with duties at Paranal Observatory Camila Navarrete; former president of SOCHIAS and recent Premio Nacional de Ciencias Exactas by the Chilean government Mónica Rubio; and ESO Astronomer Sergio Martín, manager of the Operations Performance Group at ALMA. The panel was chaired by ESO's Head of the Office for Science and Faculty chair in Chile, Itziar de Gregorio-Monsalvo.

The discussion also extended onto social media networks, where members from the local organising committee created a dedicated account for the forum and posted several questions related to the topics that would be discussed in the work-life balance session. This gave people the opportunity to comment on them, propose new topics, and vote for the questions of most interest to them.

In the first session two topics were addressed, concerning the workaholic culture in astronomy environments and the search for work-life balance when working far away from home. The competitive nature of jobs in astronomy, the tight deadlines to which we are continuously exposed, and the workaholic culture that surrounds us all serve to create significant pressures in jobs that are already quite demanding by definition. From working in the middle of an emergency or a catastrophe or going without sleep for nights and days, it is incredible what people will do to reach deadlines, which are so common and frequent in astronomy. And despite the heroic or funny anecdotes we may share with our colleagues afterwards, these sorts of pressures have a bad impact on our physical and mental health that could be addressed if we properly faced those deadlines with some better organisation. The capability to classify and set the right priorities between urgent and important tasks was considered key to survival in a world where at any moment one can receive a new message containing new requests, via multiple online channels.

Working shifts in remote places, where most observatories are, or travelling around the world several times a year to maintain international scientific collaborations or attend technical or scientific conferences makes it even more difficult to reach a healthy work-life balance. While some hobbies can be done at observatories, maintaining social relationships with outside coworkers and the family can be very challenging. In this specific matter the support and flexibility of the institutions and the need to develop specific policies to help people to reconcile work with personal life were identified as key parameters to help facilitate a work-life balance.

In the second session the importance of disconnection from work and the need to have a list of good practices at work to encourage a healthy work-life balance were discussed. Continuous online connection with work-related activities is something that has been exacerbated in the last few years because of the pandemic situation. While mobile working from home is considered good for keeping a healthy work-life balance when selected on a voluntary basis, over the long term, when it is maintained by, for example, an imposed quarantine, it can have the opposite effect and lead more easily to burnouts. Social media recently became another powerful engine for advertising, discussing, and connecting colleagues on work-related matters. Well managed, it can be a useful platform to access recent astronomy news and to build new connections in astronomy, but it impacts on the number of hours people stay connected to a computer and should also be done with awareness and for a limited time.

For those in positions of responsibility, who manage and look after a team of people, it is even more difficult to avoid being connected to the computer for too long. Since they act as role models and help to propagate the organisation's culture, they need to set a good example with their own healthy practices. An effort must be made to interact with colleagues within normal office working hours, unless there is a justified emergency case. The use of automatic tools to send deferred emails and a healthy and organised work agenda were identified as basic tools to assist in this matter.

The general conclusion of this discussion session was that "work smarter and not harder" should be a slogan adopted by all of us no matter our career stage, as the first step towards reaching a successful and healthy work-life balance while we continue contributing to the production of cutting-edge science at the observatories or at the universities. This may imply receiving training and coaching sessions to develop our time management skills and resilience, which should start from the earliest career stages. Raising awareness of the importance of disconnection was also identified as a key contributor to maintaining a good work-life balance. Those in positions of responsibility should help to maintain and promote healthy work practices, acting as role models.

The implementation of mobile working policies, aligned with people's needs and having a good degree of flexibility at work, were identified as essential ways to support work-life balance, especially for people with families.

Acknowledgements

We sincerely thank the members of the discussion panel, Carla Fuentes, Yara Jaffe, Sergio Martín, Camila Navarrete, and Mónica Rubio, for the pre-discussion session and their excellent contributions during the round table.

Zdeněk Bardon/ESO

With advanced instruments designed to catch the light from extrasolar worlds and the Universe's most distant stars and galaxies, crystal clear images are a must. To achieve this, Unit Telescope 4 (Yepun) of ESO's Very Large Telescope (VLT) in Chile has an adaptive optics facility equipped with four sodium lasers, aimed towards the sky. When the laser beams reach about 90 kilometres into the atmosphere, they excite sodium atoms that start to glow, creating artificial stars in the sky.

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Diversity, Equity, and Inclusion Round Table at the Joint Observatories Kavli Science Forum

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A diverse workforce and inclusive workspaces are critical to the advancement of science and the future of our astronomical community. Unfortunately, long-standing structural barriers prevent individuals from underrepresented groups from being fully and comprehensively represented, especially in the later stages of the career path.

As part of the Joint Observatories Kavli Science Forum, a hybrid three-hour round table was held at ESO headquarters in Chile on 27 April 2022 to exchange views on the challenges of incorporating diversity, equity, and inclusion (DEI) into the astronomical community. This article summarises the key discussions, contributions, and valuable feedback from that conversation. The panel was composed of a variety of DEI experts from Chilean observatories and organisations. Specifically, the panel included Alysha Shugart (Science Operations Specialist and diversity advocate at NOIRLab and AURA, Chile), Julio Carballo Bello (President of the Chilean Astronomical Society, SOCHIAS), Sonia Duffau (Outreach and Diversity Officer at AUI, Chile), and Steve Margheim (astronomer and member of the NOIRLab DEI Task Force).

The discussion was divided into four main sessions. First, we characterised our astronomical community based on a recent survey conducted by SOCHIAS. Second, we reflected on the underrepresentation of women and minorities in astronomy, especially in the later stages of their careers, and what is lost when the community remains unbalanced. This was followed by a brainstorming session on how to inspire, encourage, and retain women and minorities. Third, we discussed how observatories in Chile should be operated from a multicultural perspective. In this context, we emphasised the importance of working with communities near the observatories and involving them in outreach and diversity efforts. Finally, we discussed how to increase the importance of DEI in astronomy, which led to a lively debate about whether recruitment policies or training should be mandatory and who has the primary responsibility (individuals or organisations) to drive the necessary changes to ensure more inclusive institutions.

Characterising our astronomical community

Julio Carballo Bello opened the first session of the round table by presenting the results of a recent survey aimed at characterising the Chilean Astronomical Society, identifying possible problems and finding solutions. He shared demographic data that showed a significant disparity in the age distribution of men and women. The number of women, who dominate the outreach, graduate, and postgraduate student groups, decreases dramatically after the age of 40. The survey also found that 85% of participants who felt discriminated were women, 9% were non-binary, and 6% were men. While the former felt discriminated mainly because of their gender, men were more affected by social interactions and cultural differences. In addition, 20% of those who felt discriminated also felt attacked.

Following this presentation, there was some reflection on the astronomical community and the diversity of ways in which individuals can engage with it. It was agreed, however, that those who have not pursued an academic career or do not hold a PhD are not fully included. With this in mind, it was emphasised that our community is much broader, the vast majority of individuals working at observatories belonging to a wide variety of disciplines but still critical to our mission. It was stressed that it is necessary to explicitly encourage undergraduates to see the career path as a giant tree, of which only one branch ends up as a professor, at the same time adapting the curriculum to provide them with a wider and more useful skill set.

Finally, it was noted that we have very hierarchical structures and that avoiding designations could pave the way towards flatter and more inclusive organisations. Awareness and empathy were identified as the main reasons why feeling discriminated depends on belonging to a minority group. We are more likely to empathise with another person when we experience similar difficulties ourselves.

Gender and minorities within the astronomical community

The second session was introduced by Sonia Duffau, who briefly presented PROVOCA, an initiative to promote STEM careers among underrepresented groups by working with local communities and developing a mentoring programme. PROVOCA focuses on women, as that allows many other minorities to be reached because of their ‘intersectionality’ — the extent to which women are also included in other disadvantaged groups on the basis of, for example, ethnicity, sexuality, class or religion.

There was much discussion in this session about how to make committees more diverse without increasing the workload of the few minority representatives in higher positions. Some participants felt that it was important to accept these committee positions, recognising that some individuals may have to make something of a sacrifice by devoting significant amounts of their time to representing a given minority for the good of the community during a transition period. Others found it burdensome and detrimental to devote their time to such tasks instead of to research. In this framework, some solutions and considerations were proposed. First, many contributors underlined the need to reconsider candidates’ ‘requirements’. Rather than selecting from a pool of high-status women, minorities, and even men who are at a mature stage in their careers, we could select younger researchers for those panels or committees. Second, it was felt advisable to identify who else could holistically represent minority perspectives. Third, it was suggested that the power of selection be removed from the leadership by filling the positions through open calls. Finally, it was stated that we, as scientists, should educate ourselves, be aware of our own biases, and include everyone in the process, training and discussions.

Multicultural perspective: operating observatories in Chile

The third session began with Steve Margheim sharing how, while promoting the work on DEI, he has found that the burden of improving things seems to fall predominantly on the people who are most affected. DEI meetings are mainly attended by minorities, who are expected to come up with solutions; and given the low priority often accorded to such things, their efforts may even count against them. Therefore, in order to create diverse, equitable, and inclusive workplaces, institutional boards and executives need to understand and internalise that fundamental change is required for the entire structure to work.

Some participants shared the view that while the criterion typically used to evaluate a scientist's productivity (the h-index; see Fraumann & Mutz, 2020) is valuable, it does not prove everything. In this respect, it was also stressed that being grateful to our colleagues who dedicate a large part of their time to DEI is not enough. In fact, it was recommended that engagement should explicitly count with DEI as an accomplishment so that it could be career-enhancing.

With this in mind, organisations such as the Carnegie Institution for Science require grant recipients to both show interest in DEI and have a mindset that aims to bring about change. The goal is to officialise that fairness and working towards improving the community are expected and that you are also being evaluated on the basis of them. The other idea behind this is to progressively propagate this fair and inclusive mindset to higher levels. Additionally, NOIRLab has established that 3% of all employees' working time can be devoted to DEI initiatives, which means that DEI is now part of the performance evaluation process. Similarly, in order for our institutions to work in a broader community, we should also engage with the communities in which we are geographically located. We should understand their needs, their culture, and the environment in which an observatory is located, and we also need the community to engage with the mission of the observatory.

How to make DEI as important as the science we do

The final session of the round table began with Alysha Shugart summarising her experiences and lessons learned as a DEI advocate. She emphasised the importance of making any training or dialogue personal to the audience if we want them to get involved and the conversation to be effective.

In this regard, there was discussion about whether the driving force should be equity or diversity-derived benefits, and whether the responsibility should lie with individuals or organisations. It was noted that institutions that do not care enough will lose talent and will be left behind, but also that our organisations should reflect a society in which everyone has a voice and feels invited.

It was also reported that an analysis of many organisations has shown that the most successful ones are those that have DEI embedded in their mission. In this sense, the need to practice inclusion, hire empathetic leaders, and leverage the power of the solid mandates imposed by the leaders was pointed out. The importance of finding tools for accountability was also highlighted, because only when we have clear reports on the actions taken can we demand progress.

Finally, we reflected on the fact that we have grown up in a biased culture, which means we all need these trainings, conversations, and awareness-raising. Likewise, the need to be proactive and self-educate was emphasised.

This round table was a great success overall, providing an open space with a climate of respect, consciousness, and active listening where a frank exchange of views could take place. It served as a forum to discuss barriers, thoughts, lessons learned, tools, and best practices for creating a more diverse, equitable, and inclusive environment in both science and observatories.

Acknowledgements

We sincerely appreciate the invaluable contributions of Julio Carballo Bello, Sonia Duffau, Steve Margheim, and Alysha Shugart as panellists of the DEI round table.

References

Fraumann, G. & Mutz, R. 2020, in Handbook Bibliometrics, ed. Ball, R. (Berlin, Boston: De Gruyter Saur), 169

ESO/S. Guisard (www.eso.org/~sguisard)

ESO Photo Ambassador Stéphane Guisard captured this astounding panorama from the site of ALMA, the Atacama Large Millimeter/submillimeter Array, in the Chilean Andes. The 5000-metre-high and extremely dry Chajnantor plateau offers the perfect place for this state-of-the-art telescope, which studies the Universe in millimetre- and submillimetre-wavelength light.

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Report on the ESO Workshop

Solar System Science with the ELTs

held online on 28 April 2022 and at ESO Headquarters, Garching, Germany, 13–15 June 2022

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Solar System Science with the ELTs was a two-part workshop, Part I of which took place virtually on 28 April 2022, followed by Part II as a hybrid meeting at ESO headquarters on 13–15 June 2022. The main motivation for the meeting was to engage the community of Solar System observers in preparation for the forthcoming extremely large telescopes. A special emphasis was placed on exploring how ESO's Extremely Large Telescope (ESO's ELT), alongside the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), will fit into the expanding landscape of ground- and space-based facilities and transform Solar System research. The meeting brought together instrument experts and observers at all career stages, working on six continents, and representing the different sub-fields of planetary science. A Zenodo collection of the workshop presentations and discussions was publicly released to the community as a valuable resource to inspire and facilitate the development of the first extremely large telescope observing programmes. Solar System Science with the ELTs was envisaged as the first of the three-part conference series Extremely Big Eyes on the Solar System and set the stage for two further workshops in North America and Asia.

Motivation for the workshop

The launch of an outstanding line-up of telescopes and space missions over the next two decades will transform Solar System research. The three extremeley large telescopes (ELTs) will offer unprecedented observing capabilities and are expected to play a key role in shaping this landscape. With the advancing construction of ESO's ELT and its instruments, and the start of its scientific operations currently expected in 2027, the need to engage a broader community of Solar System scientists was recognised. The last workshop that focused on exploring the possibilities of studying Solar System bodies with the next-generation instruments was the INAF/Arcetri-ESO workshop on Future Ground-based Solar System Research: Synergies with Space Probes and Space Telescopes, held in 2008[1]. In the 14 years since that meeting, both instrument capabilities and the central science questions have evolved.

The Solar System Science with the ELTs workshop[2] was inspired by the success of the two previous conference series focusing on the unique capabilities of the ELTs, namely Extremely Big Eyes on the Early Universe[3] and Shedding Light on the Dark Universe with Extremely Large Telescopes[4]. To enable attendance by a broad range of participants, both of these series consisted of three consecutive meetings taking place either in Asia, North America or Europe, each with an emphasis on one of the three ELTs. Building on this experience, we set out to organise a new series focused on Solar System research, Extremely Big Eyes on the Solar System. The series took off with Solar System Science with the ELTs, hosted by ESO in 2022, and is planned to continue with two further workshops in 2023–2024.

Solar System Science with the ELTs aimed to ensure that the planetary science community, and especially early-career researchers, will be equipped with well-thought-out science goals to fully capitalise on the capabilities of ESO's ELT. Furthermore, at the time of the meeting it was still possible to adjust some instruments' parameters and their supporting software (Exposure Time Calculators, the Observation Preparation tool, etc.) to enable them to support the vast range of Solar System science cases.

This workshop also provided a timely platform to discuss the future of space missions and their synergies with the ELTs. Many space missions rely on ground-based support campaigns. And the ELTs have the potential to revolutionise the scope of that support. The ELTs will provide both sensitive observations that were previously only possible with spacecraft fly-bys, and regular monitoring of targets, otherwise requiring long-term orbiter missions. Furthermore, the workshop was planned considering the expected release dates of the ESA Voyage 2050[5] and NASA's Decadal Strategy for Planetary Science and Astrobiology 2023–2032[7]. These documents determine the science priorities and space missions available to the European and US planetary-science communities. Additionally, Solar System Science with the ELTs took place during the JWST's commissioning phase, when its actual performance was being tested and was indicating the possible synergies with the ELTs.

Workshop format

The workshop format was designed with three main goals in mind: to inform the Solar System community about the specific capabilities of the ELTs and their instruments; to encourage observers to explore potential observing programmes; and to provide feedback to the instrument development teams and involve more Solar System observers in the final steps before the ELTs become operational.

These objectives motivated the Scientific Organising Committee's (SOC) decision to divide the workshop programme into two parts. Part I of the workshop was envisaged as a technical session during which telescope and instrument experts presented the capabilities of the instruments. It was followed by a 6-week period allowing time for observers to explore the feasibility of multiple science cases of interest and to engage with the instrument teams and ELT Working Groups (WGs) in preparation for their talks. In Part II of the workshop the science presentations and discussions took place during a three-day meeting.

One other key aspect of the meeting was the SOC's intention to select talks for Part II which presented specific science cases for the ELTs. To address this, all participants registering for the meeting were encouraged to use the conference materials and Slack channel to further develop specific ideas for observations uniquely possible with the ELTs. Moreover, in an attempt to focus these efforts,

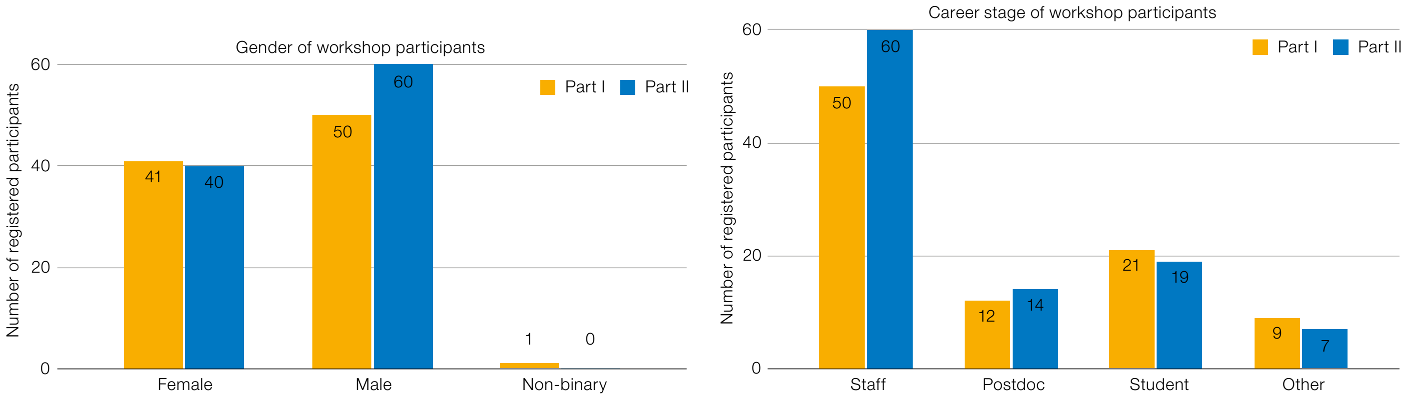

Figure 1. Distribution of the gender (left) and career stage (right) of the registered participants for Parts I and II of the workshop.

the abstract submission form required a brief description of one observing programme idea as a mock proposal for ESO's ELT.

Interaction between the workshop participants was considered essential for the success of the meeting. Rather than broadcasting the talks, the SOC and the Local Organising Committee (LOC) decided to encourage live interaction during the sessions. This was achieved by hosting the talks as live meetings on Microsoft Teams and supporting parallel discussions over Slack. For those who were not able to attend the meeting live, a Zenodo collection[7] of video lectures and selected slide decks has been curated and will remain available for free access.

The SOC and LOC wanted to reach a broader range of participants and therefore advertised the meeting to a large number of institutes in ESO Member States and worldwide. The conference was also advertised on social media, using the hashtag #SolSysELTs2022. However, the level of social media engagement was less than that of other recent ESO workshops. This was partially attributed to the relatively smaller target audience of the meeting. Even though the workshop was interdisciplinary over the scope of Solar System research, it was highly specialised when set against the scope of astronomy or physics.

Despite the fact that the meeting was timely with respect to other contemporaneous milestones of Solar System research development, the workshop was inevitably affected by the COVID-19 pandemic. The SOC and LOC were inspired to follow the models of recent ESO virtual workshops, providing a fantastic opportunity to engage a broader audience by hosting Part I of the workshop entirely virtually on Microsoft Teams and facilitating the subsequent discussions in a devoted Slack channel.

However, the pandemic had a less desirable impact on Part II of the workshop. The original intention was for Part II of the workshop to be a predominantly in-person event at ESO's HQ in Bavaria, Germany. To minimise the risks of delaying the meeting because of COVID-19 restrictions, the organisers aimed for a time of the year when the COVID-19 incidence rate was lower in Bavaria (and in the northern hemisphere more generally) during the first two years of the pandemic. To maximise participation, dates were carefully selected to avoid overlap with other major meetings relevant to the audience of this workshop.

Despite these efforts, the in-person attendance at Part II of the workshop was lower than anticipated. The COVID-19 incidence rates in many countries were rising in May and June 2022, which drove most conference participants to attend the meeting remotely. The same period in 2022 was also unusually busy with travel for many of the conference participants. Many other events had been rescheduled for 2022 and overbooked calendars were another reason to motivate online participation. These major factors (and possibly others) heavily skewed the meeting towards virtual participation. To maximise the exchange between the conference participants, the SOC adapted the programme accordingly, introducing extended discussions (of 30–60 minutes) at the end of each session during Part II. They were facilitated by a SOC member or an invited speaker and included discussions of a preplanned list of topics, as well as exchanges on other compelling questions arising during the meeting.

Special consideration was given to designing a schedule for the virtual meeting so that it was convenient for the European community but also accommodated attendance from several other time zones. Part I of the workshop included presentations from the US west coast and was therefore scheduled in the afternoon hours for the Central European Time Zone. Part II of the workshop included one afternoon, one full day and one morning on three consecutive days, and was scheduled so that participants from the Americas and from Japan and New Zealand could give their presentations at reasonable times agreed in advance with the speakers.

Workshop programme

Part I of the workshop took place over one afternoon on 28 April 2022. The programme began with a general presentation on ESO's ELT, followed by talks focusing on individual instruments (HARMONI, MICADO+MORFEO, METIS and ANDES) and their capabilities for Solar-System observations, presented by the instrument Principal Investigators. To emphasise the connection between ground-based observations and space missions, a talk on ESA's planetary science missions was presented by Luigi Colangeli. James Fanson and Christoph Dumas gave detailed overviews of the capabilities of the GMT and TMT, respectively, and the ongoing efforts to plan and develop them. All presentations were followed by sufficient time to answer all immediate questions, after which any further questions by the attendees were taken either to the meeting Slack channel or offline for private communication.

Part II of the workshop encompassed the large variety of topics studied by observational planetary science. The programme was organised into four sessions, reflecting the different populations of objects observable with the ELTs: terrestrial planets (Venus and Mars), outer planets (giant planets, their satellites and rings; tenuous atmospheres in the outer Solar System), asteroids (near-Earth, main-belt, active asteroids) and ice-rich small bodies (short- and long-period comets, trans-Neptunian objects, interstellar objects).

The sessions included invited talks, contributed talks and discussions. The invited talks provided an overview of the key questions in the given subfield and discussed how the ELTs, in synergy with current and future observing facilities and space missions, can be used to address those challenges. The contributed talks focused on specific science cases that are going to be enabled by the ELTs. Finally, each session concluded with a discussion round providing opportunities for feedback and exchange between the observers, on one hand, and those involved in the instrument and observing tool development, on the other.

This is a very brief summary of the workshop programme. We invite everyone who is interested in observations of Solar System objects with the ELTs to visit the conference website[2] for more details of the workshop programme and to explore the Zenodo collection[7] where the conference talks and discussions have been archived.

Demographics

The two parts of the workshop required separate registrations which yielded 92 (Part I) and 100 (Part II) registered participants. As discussed above, owing to the various interplaying factors, only 17 people expressed interest in attending Part II of the workshop in person at ESO's HQ, and fewer than 15 were actually able to be present during the meeting. Between the two parts of the workshop, there were participants from 27 different countries on six continents (all but Antarctica). The gender balance and career stages of the participants can be seen in Figure 1.

Ensuring diversity in terms of gender balance, career stage, nationality and ethnicity was an integral aspect of the conference organisation. The results of these efforts are partially evidenced by the gender balance among the SOC members (4 female and 6 male) and the invited speakers for Part II of the workshop (7 female and 6 male). However, we acknowledge that further efforts are strongly desirable in order to ensure equal representation in future meetings.

Concluding remarks and outlook

The idea for this conference started taking shape in the midst of the COVID-19 pandemic. The conference aimed to bring the Solar System community together in an effort to kick off the planning of observations with the ELTs. Even though most of the conference participants could not attend the workshop in person, the hybrid format of the meeting enabled effective exchange of ideas among all participants. The meeting facilitated conversations between Solar System observers and the representatives of the ELT instrument teams and working groups, thus providing the necessary input to guarantee that the instruments and their operation will provide the means to answer many essential science questions. The talks during the meeting captured the state of the art in the wide range of sub-fields in planetary science and presented a rich sample of science cases which would harness the unique capabilities of the next generation of telescopes. Additionally, the active discussions during the conference gave a platform to expand on the specific ideas discussed in the talks, and to clarify how to optimise the use of the ELTs in the existing landscape of other ground-based telescopes, space observatories and space missions in the coming decades.

A collection of all talks and discussions during Parts I and II of the meeting can be found in the Zenodo library[7]. With the agreement of all participants, these recordings have been made publicly available, and they are currently the most comprehensive resource to inform and inspire the development of observing programmes in anticipation of the fast approaching first light of ESO's ELT.

Solar System Science with the ELTs was envisaged as the first of three coordinated meetings in the Extremely Big Eyes on the Solar System series. As a meeting in Europe, this workshop provided a platform to focus on ESO's ELT and the ESA space missions. We are therefore looking forward to continuing the important discussions arising from the workshop and exploring in greater depth the capabilities of the GMT and TMT during the upcoming meetings in North America and Asia in the next few years.

Acknowledgements

We warmly thank all of the conference speakers and attendees for their active co-creation of a workshop packed with illuminating talks and discussions. We are extremely grateful to Nelma Silva, Stella Chasiotis-Klingner and Dominika Itrich for their dedication and indispensable help in ensuring the success of this workshop. We wholeheartedly thank the SOC members for their invaluable ideas and support in designing and curating this meeting, as well as for their key contribution in chairing several of the workshop sessions and discussions. We also thank Dusan Catricheo Maulén and Martin Wallner for creating the poster and visual identity materials for the meeting.

Links

1 INAF/Arcetri-ESO workshop: https://link.springer.com/journal/11038/volumes-and-issues/105-2
2 Workshop webpage: https://www.eso.org/SolSysELTs2022
3 Shedding Light on the Dark Universe with Extremely Large Telescopes: https://conferences.pa.ucla.edu/dark-universe/index.html
4 Extremely Big Eyes on the Early Universe: https://indico.ict.inaf.it/event/779/
5 ESA Voyage 2050: https://www.cosmos.esa.int/web/voyage-2050
6 Decadal Strategy for Planetary Science and Astrobiology 2023–2032: https://nap.nationalacademies.org/catalog/26522/origins-worlds-and-life-a-decadal-strategy-for-planetary-science
7 Workshop Zenodo collection: https://zenodo.org/communities/solsyselts2022/

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Fellows at ESO

Evgenia Koumpia

I've been fascinated by space ever since I was a child, something I think I owe in part to the clear, dark skies that Greece has to offer most days of the year. In 1996–1997, when I was aged about twelve, comet Hale–Bopp became visible with the naked eye from Athens. I still remember vividly how fascinated I was, and how witnessing something so beautiful in the sky (even in daytime) boosted my interest in astronomy and the mysteries of the sky even more. I became very curious about where it came from, and why it suddenly started showing two tails instead of one, but no one around me could provide answers to those questions. This is when I started to read popular magazines about astronomy and science, and the more I was learning the more I wanted to know about how stars, planets, galaxies, and the Universe itself form and behave. That was of course a child's dream but in my mind back then an unreachable one too. I didn't know what one needed to do or study to become an astronomer, or if such a thing even existed in modern Greece. At the age of fifteen a school excursion to the National Observatory of Athens helped me realise that I could in fact pursue what I had considered an impossible dream. During the observatory tour, our guide asked "...and how can someone become an astronomer in Greece?" After a few seconds of me hanging on his next words, he followed up with the answer, "one first needs to go to University to obtain a degree in physics". And that was it! This was the moment I realised that my interest in maths and physics could be put together with my genuine curiosity about space. It was then that I set my first lifetime goal — to obtain a physics degree and try to follow the path of becoming a professional astronomer.

A few years later, I started my undergraduate studies in physics at the University of Patras, where I chose, without a second thought, to follow the Theoretical and Mathematical Physics and Philosophy of Science Division, since it was the only division offering courses related to astrophysics. During the last year of my studies, I wrote an optional undergraduate thesis on the determination of fundamental parameters of planetary nebulae.

My expectations of gaining experience and knowledge through this process were fortunately fulfilled, while my love for research grew even more. After a year off, I started my master's degree in the Department of Physics at the National & Kapodistrian University of Athens in the Astrophysics, Astronomy & Mechanics section. My master's thesis, entitled "Fundamental Parameters of 4 Massive Eclipsing Binaries in Westerlund 1", on which I worked with Alceste Bonanos at the National Observatory of Athens, turned out to be the strongest motivation I ever had. Not only did I work in the same environment where I once got the inspiration and information on how to actually become an astronomer — and it is a place which remains close to my heart — but working with an active researcher gave me the advantage of getting a pretty good idea of how research works, and getting a complete picture of the procedure to be followed from the step of data analysis to the step of writing a paper. After the completion of my master's I had the great luck to be sent to the Las Campanas Observatory in Chile to perform two long observing runs (of two weeks each) as a solo observer/operator at the Swope telescope, which I still cherish as one of the best experiences of my life. This was the time that I actually felt my dream come to life and all the effort and study finally made sense; it was just me, the dome and the sky, and a huge smile on my face. This is also the point where another lifetime goal became even stronger: it was the point where I confirmed to myself that I didn't just want to become an astronomer, I wanted to become an astronomer who works at an observatory.

Soon after, I moved from Athens to Groningen in the Netherlands to start my PhD studies under the supervision of Floris van der Tak at SRON/Kapteyn Astronomical Institute. My PhD focused on understanding the physical and chemical processes that take place in regions forming both low- and high-mass stars and addressing the early evolutionary stages of star formation. To do so, I used (sub-)millimetre observations (for example, at the JCMT and the IRAM 30-metre) and sophisticated radiative transfer techniques. During my PhD years, I dealt with intellectual, emotional, cultural, and even climate challenges (naïvely, I wasn't expecting the last). And of course, during a five-year period, many things can happen in one's life that can feel a bigger burden if you live abroad. Altogether this resulted in a 15-month academic break after I obtained my PhD. During this time I travelled in Asia, worked in IBM in Groningen as a programmer/web-developer, and volunteered/trained as a Seal Rehabilitator Assistant in the Seal Rehabilitation and Research Centre in Pieterburen, a Dutch village close to Groningen. My time in IBM made me realise how much I missed working in a scientific environment, how much I missed astronomy, and how much I was diverging from my dream and my self. This made me ultimately quit my post and move to the UK where I joined the group of René Oudmaijer (to whom I am eternally grateful) as a postdoctoral fellow in star formation at the University of Leeds. During those four postdoc years, I focused on the formation of high-mass stars, an area where many open questions still exist. My studies relied, and still rely, heavily on high-angular-resolution techniques (for example, PIONIER, GRAVITY on the VLTI, ALMA).

I joined ESO in December 2021 as a fellow, with ALMA as a duty station. My research focuses mostly on observations of massive stars during their formation (but also during the final stages of their lives) at the smallest scales available, using the ESO facilities at multiple wavelengths. I chose to apply for this fellowship for many reasons but the most dominant was the distribution of science and operations time, and this is something I experience with great fulfilment. Not only can I work with ESO's state-of-the-art research facilities and carry out my research projects independently (in a sunny country), but I can combine science with operational duties at one of the world's most powerful telescopes. The observational duties of this position were and still are very exciting to me, and a very powerful drive in my professional life. And a small secret: I may currently be truly enjoying pointing antennas at the sky, but I'll always have an eye on the large mirrors too.

Carla Arce-Tord

Figure 1. Outside San Pedro de Atacama, near the APEX basecamp.

Kevin Corneilus Harrington

Recently, on Cape Cod in Massachusetts, I spoke with my high school astronomy teacher about the trajectory of one's life and the various pursuits of our bliss as human beings. He is now retired, and I happened to be the only student in his 30 years of teaching to have become a professional astronomer. He encouraged me to view my life as a mesa — with a broad mountaintop, instead of following a single journey to a single mountain peak. I can think of how this may apply to my research: for example, not just focusing on galaxy evolution but broadening to become more of an expert in the physics of the various phases of the interstellar medium, and further broadening from a focus on galaxies in the early Universe to studies of local galaxies as well. These discussions reminded me a lot about my experience in his class. Without a strong physics/maths background, his astronomy class was my main motivation for pursuing a degree at the University of Massachusetts, Amherst (UMass). I studied there and also received a separate degree in Psychological and Brain Sciences. Science is interconnected in so many ways, and the disciplines of study within neuroscience provided a unique insight to compare with astronomy and astrophysics.

I have always been connected to radio astronomy. At the time I arrived as a student at UMass, the world's largest single-dish submillimetre telescope was just being constructed after decades of discussion: the 50-metre Large Millimeter Telescope (LMT) in Mexico. My first internship was at UMass, during the summer after my first year. I matched the catalogues of the Herschel and Planck submillimetre space telescopes. I identified candidate sources to follow up during the commissioning phases of the LMT and went to Mexico to observe for the first time the following year. My supervisor and I detected CO emission from our target sources, placing them at a distance corresponding to roughly 11 billion years ago and confirming them as some of the most infrared-luminous objects on the entire sky.

The next summer was spent in Puerto Rico at the Arecibo Observatory — which has now unfortunately collapsed. I remember playing my box drum 'cajon' almost daily down by the 300-metre-diameter dish. That summer I studied massive star-forming complexes within the W51 region of our Milky Way galaxy and learnt how to reduce and analyse spectroscopic radio data to identify hydrogen radio recombination lines.

My final summer as a university student was spent in Green Bank, West Virginia in the heart of the radio-quiet zone region of the United States. Here I worked as a summer student for the National Radio Astronomy Observatory at the Green Bank Telescope (GBT), now the Green Bank Observatory. For my project there, I was able to look at the centre of the Milky Way using data from the 100-metre GBT. The idea was to further identify hydrogen clouds that are entrained within an outflow from the Milky Way; evidence from the ATCA telescope in Australia had first pointed towards this peculiar population of high-velocity clouds that are not following the galactic rotation. My supervisor in Green Bank had an established collaboration with the group in Australia and obtained more data for me to dig into, which eventually led to a publication down the road.

While at Arecibo my mentors had encouraged me to consider applying for a PhD programme in Europe — specifically pointing my attention to the International Max Planck Research School (IMPRS) for astronomy and astrophysics in Bonn, Germany. I kept this in the back of my mind and continued working on what would become my first lead author publication while finishing my studies at UMass. This paper had formally presented the LMT detections dating back to when I was a very young student confirming the target list during my observations in Mexico. This publication set the stage for future follow-up because: 1) there were many more targets than there were in this pilot study; 2) these objects are gravitationally lensed, offering unique observational advantages to study the interstellar medium of galaxies in the early Universe; and 3) they are intrinsically gas- and dust-rich, and forming a plethora of stars, such that they truly are some of the brightest objects on the sky.

I had applied to do my doctoral studies at the IMPRS, which partners with the Max Planck Institute for Radio Astronomy in Bonn, the Argelander Institute for Astronomy of the University of Bonn and the Physics Institute of the University of Cologne. After receiving an offer, I decided I would go, and it was where I was encouraged to apply two years before. I hit the ground running with lots of lead-author proposals to keep pursuing these bright, dusty starburst galaxies and developed a systematic study of their molecular gas content as a focus for my thesis work. In over four years in Bonn I was able to travel to the IRAM 30-metre telescope in Spain and the APEX telescope in the Atacama desert in Chile to observe and acquire first-hand experience observing the invisible skies at millimetre wavelengths.

It was while at APEX that I spoke to one of the long-time operators about my next steps. He encouraged me, in a very Chilean manner, to definitely apply for the ESO Fellowship. I knew that observations are at the heart of who I am as a person — I observe when I meditate, I meditate while I observe, and I enjoy the process and adventure involved with each observing run. The ESO Fellowship allows me to continue this, as sustained observations and operations are at the core of ESO. The balance that comes into the equation of observing duties and focused science research is something that is always being navigated. I have had amazing experiences being able to go to observe at APEX and ALMA in the past year and a half — with breathtaking views of what looks to be Mars, but it is in fact our planet Earth. I am always inspired to do more science as I am observing, and if there is a quiet time during the observing shift I will play my djembe or another small hand drum and think about how wonderful it really is to be paid to do this: to go and observe and study the Universe.

What was initially a pilot study during my university studies has led to more than the basis of my PhD research. It has now grown into an international collaboration with multiwavelength datasets spanning all the major optical/radio/submillimetre facilities, named the Planck All-Sky Survey to Analyze Gravitationally lensed Extreme Starbursts (PASSAGES) — which I am now leading as project manager. The ESO Fellowship has allowed me to strike the balance between developing my career and my role as an experienced observer, providing the freedom and flexibility to be an independent researcher. I am looking forward to continuing this work for the next two years, and to meeting others who may end up being more lifelong friends.

ESO/B. Tafreshi (twanight.org)

ESO operates the Atacama Pathfinder Experiment, APEX, at one of the highest observatory sites on Earth, at an elevation of 5100 metres, high on the Chajnantor plateau in Chile's Atacama region. APEX is a 12-metre-diameter telescope, operating at millimetre and submillimetre wavelengths — between infrared light and radio waves. Submillimetre astronomy opens a window onto the cold, dusty and distant Universe, but the faint signals from space are heavily absorbed by water vapour in the Earth's atmosphere. Chajnantor is an ideal location for such a telescope, as the region is one of the driest on the planet and is more than 750 metres higher than the observatories on Maunakea, and 2400 metres higher than the Very Large Telescope (VLT) on Cerro Paranal.

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Engineering Fellows at ESO

ESO's core mission is to build and operate state-of-the-art facilities for the advancement of astronomical research and to foster international cooperation for astronomy. A strong research and development programme is therefore at the core of ESO's activities. For this reason, for a few years ESO has established, in addition to the ESO fellowship programme for researchers in astronomy, an engineering fellowship programme. The profile of one of these ESO engineering fellows is presented here.

Petr Janout

A person close to me once asked what I thought about the Universe. I could have said that it's something bigger than all of us and then asked a rhetorical question about how our own problems relate to the Universe at large. But my reply was that the Universe is something that keeps us focused throughout our lives because it is an endless well of knowledge. That question, however, still comes to my mind from time to time.

My choice of field of study led me to the Czech Technical University in Prague, where I started along the path of becoming an electronic engineer. During my studies, however, I began to move more and more into the field of optics and photonics. Light, lasers, and photons brought another dimension to the electrical field, as it was possible to see what light does in different materials and how it interacts, and how light is perceived by human beings. Therefore, when finishing my engineering studies, I decided to get involved more deeply in optics and photonics and so I decided to join a photonics research group.

From the beginning of my PhD work, I focused mainly on the deformation of the wavefront of extremely wide-field-of-view imaging systems. The main question was whether we could mathematically describe all-sky monitors well enough to retrieve useful astronomical data and use an all-sky camera to observe and forecast upcoming natural disasters in the form of torrential rains or other observable meteorological events. In parallel, our group has worked on interesting topics involving crystalline materials that can be used for light- and acoustic-wave interactions. This research sparked my curiosity about what we can do with photons. As soon as the opportunity to join ESO occurred, I was especially interested to start working on larger-scale optics and to begin looking deeper into the Universe.

The opportunity to join ESO came from the Czech Ministry of Education, Youth and Sports through a dedicated training programme for Czech students and interns at ESO. I got involved in finding solutions to the issues affecting large-scale and complex optics as regards the alignment of segmented mirrors during and after the maintenance of a segment. I also explored the potential of spatial light modulators in the application of large-scale optics. This initial period at ESO drove me to the decision to apply for an ESO Engineering Fellowship and continue the exciting work I'd found myself doing. I was driven by an interest in exploring and expanding my awareness of the applications of spatial light modulators. With a bit of creativity, they can be used in many ways where the phase of the modulated light becomes an important consideration. This, however, is only a small part of my ongoing work at ESO.

At ESO I am also involved with the CaNaPy project, which is a pioneering laser guide star (LGS) adaptive optics (AO) facility to experimentally explore novel schemes for visible-light AO corrections. I am involved in the optomechanical design, the alignment, and the testing of the optics used at the CaNaPy facility. When the CaNaPy bench is installed at the OGS telescope in Tenerife, we will use it to explore and demonstrate optimal LGS-AO performance at visible wavelengths and in harsh seeing conditions. This will include operating the LGS AO during the much harder daytime conditions and attempting the retrieval of atmospheric tip-tilt from the LGS beacon itself.

Working on amazing projects is of course simply a part of everyday life. When the time comes to leave a city, I like to be lost in nature and enjoy the beauty and silence of the mountains. A camera is then my favourite toy to capture the memories of the moment.

Message from the Editor

The Messenger to Become an Online-Only Publication

Mariya Lyubenova[1]

[1] ESO

Since its launch in May 1974, The Messenger has provided a regular stream of information about ongoing developments at ESO. Started originally with the primary goal of serving as an internal communication channel for ESO, nowadays its scope extends far beyond that. Today The Messenger serves as a link between ESO and its broad astronomical community by providing information about scientific, technical, and other developments. It also delivers relevant news about astronomy and astrophysics to a broader public, including policy-makers, government officials, journalists, teachers, and amateur astronomers, as well as to interested scientists from other fields.

Together with the evolution of its scope and content, The Messenger has also undergone an evolution in the way in which it has been reaching its readers. Starting with a printed-only version in 1974, the first digital issues saw their first light in the 2000s, and gradually the complete archive of the journal has been made available to the community in digital form, enabling greater accessibility, usability, and traceability of the published articles.

Following recent developments in journal publication practices and the gradual change in the habits of our readers, as well as with sustainability in mind, ESO has decided that as of 2023 The Messenger will become an online-only publication. We invite our readers who wish to receive the new issues directly into their email inbox to subscribe using the link provided on The Messenger webpage[1]. We also take this opportunity to inform our readers that, owing to resource limitations, there will be only two issues published in 2023, in the spring and in the autumn.

Links

[1] The Messenger webpage: https://eso.org/messenger/

This picture shows the spiral galaxy NGC 986 in the constellation Fornax (The Furnace). The galaxy, which was discovered in 1826 by the Scottish astronomer James Dunlop, is not often imaged owing to its proximity to the famous and rich Fornax Cluster of galaxies. This is a shame, as this galaxy is not only a great scientific object, but also very pretty. This image was taken with the FORS instrument on ESO's Very Large Telescope at the Paranal Observatory in northern Chile.

The Cone Nebula is part of a star-forming region in space, NGC 2264, about 2500 light-years away. Its pillar-like appearance is a perfect example of the shapes that can develop in giant clouds of cold molecular gas and dust, known for creating new stars. This dramatic new view of the nebula was captured with the FORS2 instrument on ESO's Very Large Telescope (VLT), and released on the occasion of ESO's 60th anniversary.