The Messenger

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2018 Visiting Committee Report
SPHERE Unveils the True Face of the Largest Main Belt Asteroids
The ASPECS Survey

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

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Front cover: The unique capabilities of the SPHERE instrument on ESO's Very Large Telescope have enabled it to obtain the sharpest images of a double asteroid as it flew by Earth on 25 May 2019. While this double asteroid was not itself a threatening object, scientists used the opportunity to rehearse the response to a hazardous Near-Earth Object (NEO), proving that ESO's front-line technology could play a key role in planetary defence. This artist's impression shows both components of the double asteroid 1999 KW4 during its Earth fly-by. Credit: ESO/M. Kornmesser

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The 2018 Visiting Committee Report

Hans-Walter Rix [1]

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ESO's activities are externally assessed every few years by a Visiting Committee composed of a panel of senior external experts who report their findings to the ESO Council and Director General. The assessment is based on an extensive set of presentations, reports and interviews with ESO staff conducted during visits to all ESO sites. Here we summarise the report and recommendations produced as a result of the latest Visiting Committee assessment, which took place at the end of 2018 and was presented to the ESO Council in June 2019.

The ESO Visiting Committee (VC) offers its external assessment of how ESO is complying with its mission to provide world-class facilities for astronomy and to foster astronomical collaborations. To this end, the VC considered the competitiveness of the research carried out by the ESO community and evaluated the calibre and range of ESO's observatory activities. The VC also looked at ESO's organisational health and readiness to reach its strategic goals, in particular the implementation of the Extremely Large Telescope (ELT) programme.

This report is based on the VC's two site visits — carried out between 22 and 26 October and 19 and 27 November 2018 in Garching and Chile, respectively — and extensive materials provided before and during these site visits. The report was informed by numerous direct interactions with ESO staff at all levels of the Organisation. All of the main recommendations reported here reflect consensus within the VC.

The VC came to the conclusion that, at present, not only is ESO fulfilling the essential elements of its mission superbly, but it is also a beacon of science in Europe and the world and a global leader in astronomy. Internally, ESO is a strong and largely healthy organisation, with strains and issues at a level that is to be expected for an endeavour of this ambition, complexity and history. Looking to the future, the VC concluded that ESO is indeed set for a successful implementation of the ELT if the Organisation — and its Council — address a number of challenges, some of which are pointed out in this report.

ESO's strengths and excellence

The VC found ESO to be a world-class science organisation, truly exceptional in many respects. It has implemented and is operating a suite of observatories and instrumentation that is unrivalled in its combination of quality and breadth; the success of the Very Large Telescope Interferometer (VLTI) with the adaptive-optics-assisted, two-object, multiple beam-combiner GRAVITY is just one example. ESO's facilities enable its user community to carry out astrophysics on a par with other world-class facilities. The VC notes that Atacama Large Millimeter/submillimeter Array (ALMA) astrophysics carried out by the ESO community is truly outstanding at a global level.

The basic organisational structure within ESO is suited to its tasks, and it has a track record of adapting to new challenges. ESO can also draw on a deep pool of talent; the VC found a high level of staff dedication to its mission, and generally high employee motivation with a positive gradient.

The VC found that, in looking towards the future, ESO leadership appears to be striking a good balance between ambitious vision, dedication to excellence in its observatory facilities and moving towards healthy planning realism.

Optimising ESO's organisational structure

In light of these strengths, the VC paid particular attention to the question of whether ESO is ready to implement the ELT in the coming decade while continuing to maintain its cutting-edge strengths at the existing observatories (i.e., the La Silla Paranal Observatory) and sustaining its strong role in ALMA. It is the VC's view that ESO can accomplish this, as there are no obvious show-stoppers, and that it will succeed if a number of challenges are successfully met. ESO is aware of those challenges, and some of them have been emphasised in the VC's recommendations.

ESO should continue to optimise its organisational health and efficiency by: strengthening both strategic planning of, and agility in, personnel recruitment and fostering in-house mobility; ameliorating both overbooking and project-multiplexing among individual staff members; ensuring that long-term planning security for ELT key expertise remains feasible within the matrix framework; and continuing to improve the communication flow, both upwards and downwards, within the Organisation.

ELT implementation

The VC was very impressed with the state of the ELT planning and implementation, as well as ESO's awareness of the complexity and enormity of this ambitious project. In light of the complexity, the VC recommends that ESO pay even closer attention to two aspects. First, a tightly integrated telescope-instrumentation-operations approach is key to the timely success of the ELT and an important aspect of mitigating budgetary and scheduling risks; these three aspects of the ELT must be tied together even more closely than in the case of the Very Large Telescope (VLT). Second, strong and coherent scientific leadership of the overall ELT effort must be in place throughout its implementation.

The VC also considered other aspects of ESO, such as its outreach strategy and the involvement in the Atacama Pathfinder EXperiment (APEX) and the Cherenkov Telescope Array (CTA).

Summary of recommendations

Articulating the current ESO strategy

ESO has successfully implemented most of the strategic vision that was laid out in 2004. The VC recommends that the ESO Council and the Director General develop and formally document ESO's strategic vision for the next decade. The VC strongly supports ESO's overriding focus on the implementation of the ELT while maintaining current strengths. The VC therefore acknowledges and supports the conclusion that any responsible articulation of the current strategy may leave little or no room for the implementation of any other major new programmes in the near future.

Ensuring the budget envelope for ESO's mission

The VC appreciates ESO's current rigour and realism in determining the resources needed for the implementation of the ELT. It is the VC's view that, as an organisation, ESO is robust and efficient enough to successfully implement the ELT within the currently forecast resource need, which strains the contribution envelope of the Member States. The VC strongly encourages the ESO Council to push for the provision of the required (forecast) budget, as this will indeed ensure ESO's global leadership in astronomy for decades to come.

Optimising ESO's organisational health and efficiency

The VC found ESO to be a strong, healthy and efficient organisation overall, with highly talented and motivated staff. The organisational strains that will inevitably result from ESO's ambitious plans will require continued and strengthened effort towards organisational optimisation.

Specific recommendations follow:
- The VC recommends that ESO continue to address or mitigate both the historic and the inevitable political differences in its staff arrangements, such as aspects of the 50/50–80/20 science/duty contracts for scientists, or aspects of the international/local staff categories among technical and scientific staff in Chile.
- The optimisation of the matrix structure at ESO Garching, which has gained widespread acceptance, must continue by: eliminating or reducing oversubscription of staff resources; addressing the extensive project fragmentation experienced by some staff; and finding ways to assure long-term planning security for key ELT expertise within the matrix framework.

Strategic and efficient recruitment

Among aspects of organisational efficiency, extensive near-term recruitment of highly qualified personnel will be key to ESO's mission success in the coming years. The VC recommends that ESO review all aspects and all actors involved in efficiently and successfully bringing in new talent; this is to ensure that recruitment is both proactive and strategic, as well as efficient and rapid in practice. The VC also recommends that ESO continue to improve the effectiveness of in-house career mobility and development.

A close telescope-instrumentation-operations approach for the ELT

In light of the ELT's complexity, the VC recommends that ESO pay close attention to a very tightly integrated telescope-instrumentation-operations approach. In the VC's view, this is key to the timely success of the ELT and is an important aspect of mitigating budgetary and scheduling risks. Specifically, the VC recommends that the ELT Programme deepen its connections with both the external instrument teams and the future LPO operations team, in a spirit of close collaboration.

Overall science leadership for the ELT

The VC recommends that ESO ensure strong science leadership of the overall ELT effort as it will be critical to the ELT's long-term scientific success and impact. Such leadership is key to fully considering the needs of the telescope, the instruments, the AO and the operations from the viewpoint of the ELT's overall scientific utility; it will also ensure that appropriate trade-offs are made between performance and capability on the one hand, and budget, schedule and risk on the other.

On CTA implementation

The VC concurs with ESO that CTA is an exciting scientific prospect in collaboration with a strong consortium. The VC is also concerned that unforeseen efforts related to CTA on ESO's part could distract from the implementation of the ELT and strongly recommends that ESO's prioritisation, role and effort in CTA do not grow beyond what is currently planned.

On the future of APEX

APEX is currently working well and producing good science. The VC recommends that ESO examine critically whether APEX will remain scientifically indispensable for its user community as ALMA matures, beyond the current contractual arrangement.

On education and outreach strategy

The VC recommends that ESO clarify and strengthen its vision, and implementation, of its education and outreach effort, with a closer integration and coordination of these activities in Europe and Chile. In Garching, the VC sees a serious risk that the tremendous potential of ESO's Supernova will not be realised, given its current lean level of staffing. The VC was unconvinced that augmenting the current operations model merely by external fundraising alone would lead to an education and outreach effort that lives up to ESO's vision.

Note

[a] The Visiting Committee 2018 was composed of Masimo Altarelli, Rebecca Bernstein (Vice-Chair), Sofia Feltzing, Robert Kennicutt, Anne-Marie Lagrange, Hilton Lewis, Elena Pian, Hans-Walter Rix (Chair) and Patrick Roche.

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Following Up on the Recommendations of the Visiting Committee

Xavier Barcons [1]

[1] ESO

Like most scientific organisations, ESO periodically invites advice from an external expert panel that assesses the performance of the Organisation, and formulates a number of recommendations. The most recent ESO Visiting Committee travelled to all of the ESO sites in the last months of 2018 and delivered its report to Council in June 2019. The committee, whose composition and mandate had been approved by ESO Council, was constituted by a set of internationally renowned scientists who possess complementary areas of expertise covering all aspects of ESO's function. I am extremely grateful to all committee members for their hard work and very careful preparation of their report. An extract of the main conclusions and recommendations is presented in the preceding article.

The ultimate goal of this exercise is to obtain external and expert guidance on areas where action needs to be taken, at the very least because there is always room for improvement. However, as a member of ESO, it is also rewarding to read in the report that in the committee's view ESO is fulfilling its mission very well, and that with the support of Council and the adoption of a number of recommendations the Organisation is bound to succeed in its current endeavour, that of building and bringing into operation the ELT, while maintaining the VLT/I and ALMA at the forefront of worldwide astronomy. It gave me great pleasure to convey the congratulations of the Visiting Committee to all ESO personnel.

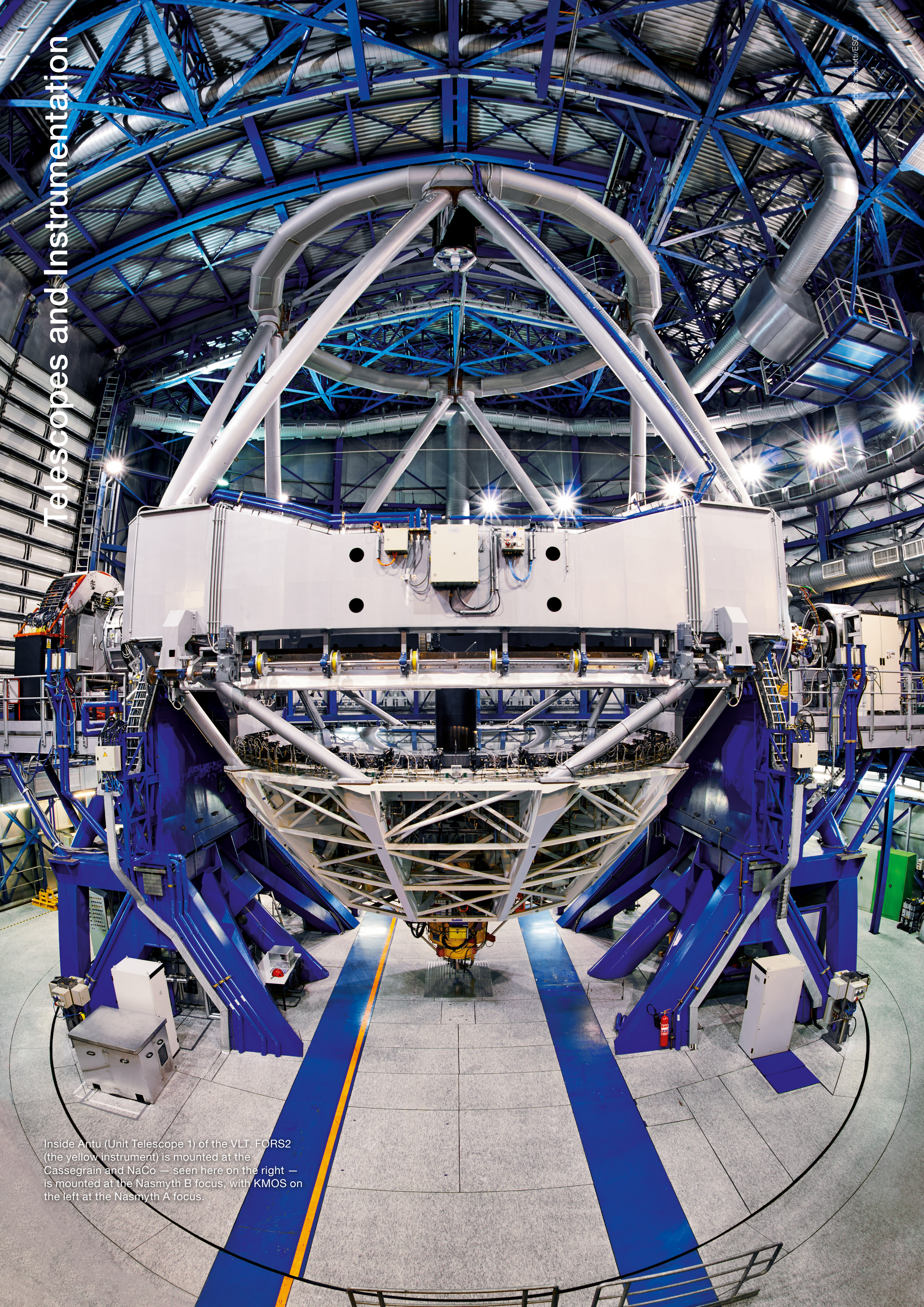
A number of actions aligned with the Visiting Committee recommendations are now being taken after discussion with the ESO Council. Updates on these actions will be reported to and discussed with Council as they progress. The ongoing actions include: support to ESO Council in discussing an updated strategy; a careful and continuous updating of the risks and costs of building the ELT and bringing it into operation; continuing to recruit the necessary staff to support the ELT — avoiding overloading and project fragmentation in the matrix; intensifying the understanding between ELT construction and Paranal operations as well as enhancing ESO's technical involvement in ELT instrument development; empowering and further supporting the ELT Programme Scientist in overseeing all scientific aspects of the ELT; clarifying the interfaces with CTA-South to ensure that the project develops without affecting the other projects in Paranal; discussing the future of the Atacama Pathfinder EXperiment (APEX) in a cost-neutral way for ESO and defining a communication strategy that capitalises on ESO's scientific achievements and the added value of ESO's programmes to society.

I have no doubt that the recommendations of the Visiting Committee will strengthen ESO and increase the likelihood that it succeeds in its mission.

ESO/B. Tafreshi (twanight.org)

Paranal Observatory with the Milky Way appearing to stretch directly upwards from one of the Unit Telescopes.

Telescopes and Instrumentation



Enrico Sacchetti/ESO

Inside Antu (Unit Telescope 1) of the VLT. FORS2 (the yellow instrument) is mounted at the Cassegrain and NaCo — seen here on the right — is mounted at the Nasmyth B focus, with KMOS on the left at the Nasmyth A focus.

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NaCo — The Story of a Lifetime

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NaCo was switched off on 2 October 2019, almost 18 years after its first light. The last exposure was of the standard star HD590 as part of the close-out calibrations. To date, 699 papers have been published using NaCo data, including observations of the Galactic centre, direct images of exoplanets orbiting their stars, young stellar objects, brown dwarfs, massive stars, stellar clusters, Solar System objects, SN 1987A and several extragalactic sources. We present a short history of the life and achievements of NaCo from the viewpoint of the Instrument Operation Team, Instrument Scientists, and Instrument Engineers.

Introduction

The Nasmyth Adaptive Optics System (NAOS) was developed by a French consortium[a] in collaboration with ESO, and the COudé Near-Infrared CAmera (CONICA) was built by a German consortium[b] in collaboration with ESO. Together they form NAOS-CONICA (NaCo) which was the first instrument with an adaptive optics (AO) system on the Very Large Telescope (VLT). It was first installed at the Nasmyth B focus of UT4 (Yepun), where it stayed from 2001 through 2013. In 2014 it was reinstalled on UT1 (Antu) at the Nasmyth A. Early tests and results from commissioning runs showed that, by compensating for a large fraction of the atmospheric turbulence, it could obtain spatial resolutions close to the 8-metre telescope's diffraction limit. The AO system was equipped with both visible and infrared, Shack–Hartmann type, wavefront sensors; the latter enabled observations inside regions that are highly obscured by interstellar dust and therefore unobservable in visible light. For almost 18 years, NaCo provided multimode, AO-corrected observations in the 1–5 μm range.

The odyssey begins

Numerous boxes containing the many parts of NAOS and CONICA arrived at ESO's Paranal Observatory on 24 October 2001. Astronomers and engineers from ESO and the participating institutes and organisations[a, b] began the painstaking task of assembly on the Nasmyth B platform of UT4 (see Figure 1). After days of technical tests and adjustments, working around the clock, the team finally declared the instrument fit to attempt its first-light observation.

The UT4 dome was opened at sunset on 25 November 2001 and a small, rather apprehensive, group gathered in the VLT Control Room, peering intensively at the computer screens over the shoulders of their colleagues the telescope and instrument operators. As the basic calibrations required at this early stage were successfully completed, the suspense rose, as did expectations as the special moment approached when finally the telescope operator pushed the button that sent the telescope towards the first test object, an otherwise undistinguished star in our Milky Way.

The uncorrected image was recorded by the near-infrared imager and spectrograph CONICA and it soon appeared on

Figure 1. NAOS (light blue) and CONICA (red) are attached to the Nasmyth B adapter of UT4 (Yepun). The control electronics are housed in the white cabinets.

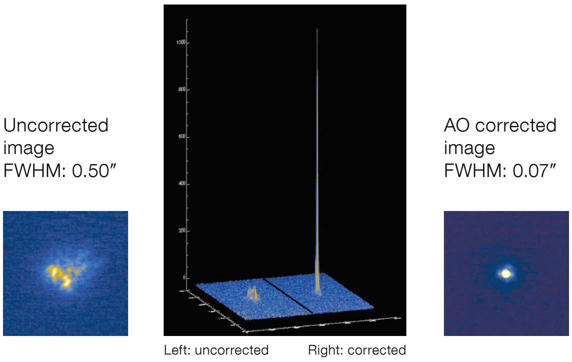
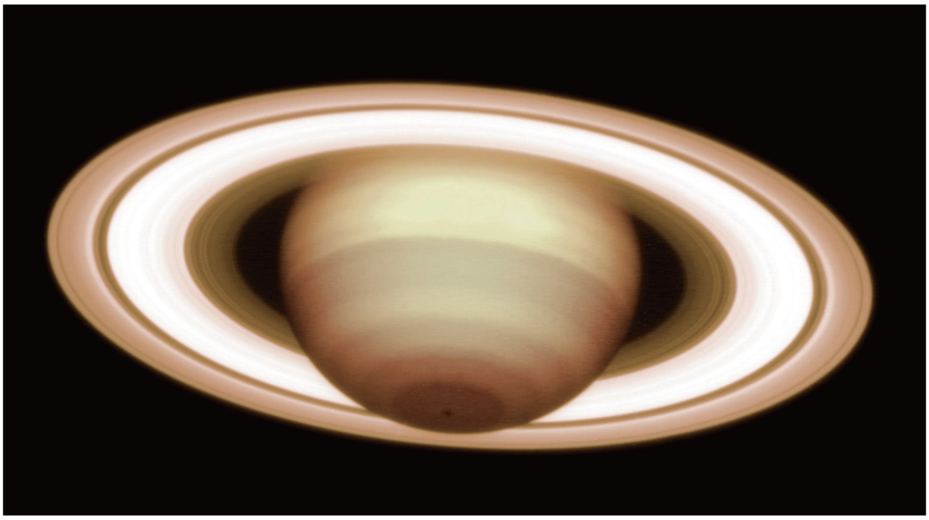


Figure 2 (left). The first image with NAOS-CONICA of a star (*V* magnitude of 8) obtained before (left) and after (right) the adaptive optics was switched on.

Figure 3 (below). The giant planet Saturn as observed with the VLT NAOS-CONICA Adaptive Optics instrument on 8 December 2001.



ESO/S. Gillessen et al.

Figure 4. The central parts of our galaxy as observed in the near-infrared with NaCo. By following the motions of the most central stars over more than 16 years, astronomers were able to determine the mass of the supermassive black hole in the centre.

the computer screen. With a full width half maximum (FWHM) diameter of only 0.50 arcseconds, it already showed good image quality, thanks to the atmospheric conditions on that night. Then the NAOS adaptive optics system was switched on, thereby "closing the loop" for the first time on a celestial object. As the deformable mirror in NAOS began to follow the "orders" that were being issued 400 times a second by its control computer, the stellar image on the computer screen seemed to pull itself together. What seconds before had been a jumping, blurry patch of light suddenly became a rock-steady, razor-sharp and brilliant spot. The entire room burst into applause with happy faces and smiles all round. Nowadays, we are used to getting these sharp and steady images whenever the loop of an adaptive optics system closes. But at the time of NaCo's first light, this must have been a truly magical moment. The diameter of this first image was measured as 0.068 arcseconds (see Figure 2).

Even during those early tests and commissioning nights, NaCo delivered impressive astronomical results. Among the first images to be obtained was one of the stellar cluster NGC 3603, a high mass star-forming region. Only with the new, high-resolution *K*-band images was it possible to finally study the elusive class of brown dwarfs in such a starburst environment. Another early highlight was the observation of Io, the innermost of the four Galilean moons of Jupiter and the most volcanically active place in the Solar System (see press release eso0204[1] for details). And then of course, there was the "Lord of the Rings", Saturn itself, in all its beauty. These observations were very challenging. CONICA's field of view had to be steadied on Saturn, NAOS had to track the small moon Tethys, the reference source for the adaptive optics, and UT4 was tracking a star used for determining active optics corrections and autoguiding. As Figure 3 shows, it worked.

However, the commissioning itself was also under a lot of pressure. Firstly, there was strong competition for precious console places because the fibre positioner for FLAMES was being commissioned at the same time. Secondly, the centre of our Galaxy becomes observable in April and NaCo was supposed to start monitoring this region. There was a big rush to get NaCo operational in time for an early epoch observation. In fact, NaCo turned out to perform excellently (see Figure 4) and it became a key instrument for monitoring the motions of the stars close to the Galactic centre for many years. By measuring these stellar orbits with such amazing precision, it was possible to conclude that the central invisible object is very likely to be a supermassive black hole (Gillessen et al., 2009).

The early years

Not everything worked immediately though and that's why NaCo is also a story of encounters and friendships between astronomers, amazing engineers and dedicated telescope operators. From the beginning, the instrument appeared to have its own moods and people had to comply with these to successfully operate NaCo and keep it observing through the night. Sometimes it just didn't work, often it required enormous effort and collaboration between various departments to get it up and running. Only with time and improved monitoring were these moods attributed — at least to a large degree — to specific atmospheric behaviour. In this way, NaCo also taught us the importance of monitoring and recording ambient physical properties as well as instrumental performance, now regular practice with all instruments.

Then there have been all the unforeseen circumstances: when the only NaCo-trained night astronomer fell sick just before the first visiting observer run, and a colleague had to take over at the last minute; when, in the aftermath of NASA's Deep Impact mission[2], NaCo broke down just before the time-critical observations, was urgently fixed and was still cooling down at the most crucial moment; and when the NAOS field selector broke, requiring two intensive weeks on the mountain to repair it. The Instrument Scientist at the time also vividly remembers the time when UT4 was observing with the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) under wonderful conditions and they needed to check some NAOS connection. They opened one of the cabinets and caused a complete shutdown of the telescope — and a shock for everyone involved.

On the other hand, there have been numerous special moments, like the Pluto occultation, when astronomers, operators, engineers and everyone else were all waiting enthusiastically for the event,

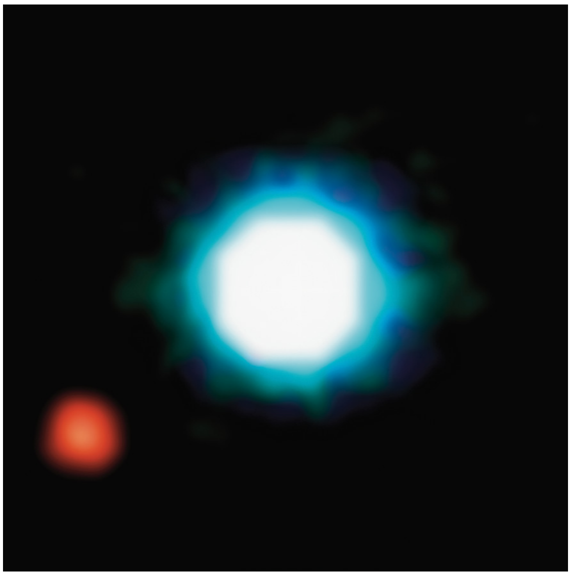


Figure 5. This composite image shows an exoplanet (the red spot on the lower left), orbiting the brown dwarf 2M1207 (centre). 2M1207b is the first exoplanet directly imaged and the first discovered orbiting a brown dwarf. It was imaged for the first time with NaCo on UT4 in 2004.

but also very nervously as it was not clear whether Paranal was in the right viewing zone. When the event did happen, the tension broke and the visiting astronomer started applauding and kissed his wife. Afterwards everyone involved celebrated with excellent French cheese the smell of which lingered until the next day.

Another of these special moments was the observation of 2M1207, a brown dwarf in the young TW Hya association. In a series of NaCo exposures, a tiny red speck of light was discovered only 0.8 arcseconds away from 2M1207 (see Figure 5). The thrill of seeing this faint source of light in real-time on the instrument display is indescribable. Was this actually a planet orbiting the brown dwarf? A spectrum taken with NaCo shows the signatures of water molecules and confirms that the object must be comparatively small, cold and of about five Jupiter masses. However, to prove that it is a planet orbiting the brown dwarf, more images over a longer time interval had to be obtained. Only a year later, it was confirmed that indeed NaCo had taken the first image of a planet outside our Solar System (Chauvin et al., 2005).

New observing modes

After several years of operation, a number of previously planned upgrades to NaCo were carried out (Kasper et al., 2005). These included the low-resolution prism which allowed simultaneous spectroscopy from *J*- to *M*-band, the installation of order-sorting filters that allowed *L*-band and *H*+*K*-band spectroscopy at various spectral resolutions, and the Fabry-Perot interferometer to take narrow-band observations tunable between 2 and 2.5 μm. Also the detector was upgraded, the new Aladdin III detector having better cosmetics, linear range and readout noise.

However, the NaCo instrument concept was always considered a flexible one, and this triggered new ideas about how to extend and optimise the capabilities of NaCo, especially for certain astronomical applications. For example, exoplanets, where for any kind of direct imaging the main problem is the high contrast between the light of the host star and the light of the planet. Of course, larger planets are easier to observe, as are planets around faint stars. It is no surprise that the first imaged planet was a giant, Jupiter-like planet around a brown dwarf. To decrease the contrast between star and planet, new modes were invented, such as simultaneous differential imaging (Lenzen et al., 2004), the four-quadrant phase mask together with a Lyot-Stop coronograph (Boccaletti et al., 2004), a pupil stabilised mode for Angular Differential Imaging (Kasper et al., 2009), the Apodising-Phase-Plate coronograph (Kenworthy et al., 2010), and the Annular-Groove-Phase-Mask (AGPM) coronograph (Mawet et al., 2013). NaCo served as a testbed to implement and evaluate all of them.

Other attempts were made to increase the spatial resolution and get down to the diffraction limit with a well calibrated point spread function. The interferometric mode using Sparse Aperture Masking (SAM; Lacour et al., 2011) as well as speckle holography (Schödel & Girard, 2012) and speckle imaging without AO (Rengaswamy et al., 2014) served in this respect and broadened the possibilities for NaCo science cases.

One of the major changes on Paranal in general but especially for NaCo and SINFONI was the installation of the first Laser Guide Star (LGS) facility, a collaboration between ESO and MPE. NaCo had to be upgraded for the extended spot of the LGS. A System for Tip-tilt Removal with Avalanche Photodiodes (STRAP) was installed, along with a new laser dichroic and a new wavefront sensor lenslet array with a larger field of view. The NaCo upgrade for LGSF was a collaboration between the Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) and ESO, led by Gerard Zins who was at IPAG at that time (Kasper et al., 2010). Again, the collaboration made all the difference and much fun was had working with the Garching AO group installing the laser. Even the non-AO astronomers vividly remember being involved in the first nights of laser observations. Because the automated plane detection software had not yet been approved for safety, everybody was helping out with plane spotting, standing outside with a radio on the telescope platform, watching the sky, and sending the stop-propagation order if a plane was getting too close.

Dear outstanding professionals,

two nights ago our NACO had the last whisper on sky after observing a bright star.

It's been more than 20 years of amazing science and unique achievements!!

Together we've seen things you people wouldn't believe.
Engineers fighting their way through dichroics and wave front sensor. Astronomers worshipping a closed loop with seeing 2.0″ and coherence time 0.5 ms.
We watched violent storms on Jupiter's pole, planets orbiting desolate stars, Galactic Center glittering in the dark.
All those moments will be lost in time, like tears in rain.
Time to die.

Your sincerely,
Antu on behalf of NACO

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Estimados colegas,

dos noches atras NACO dio su ultima mirada al cielo.

Fueron mas de 20 años de maravillosa ciencia y resultados unicos!!

Juntos vimos cosas que ustedes no se pueden ni imaginar.
Ingenieros enfrentandose con dicroicos y sensores de frente de onda.
Astronomos cerrando el loop en condiciones proibitivas.
Hemos visto tempestas al polo norte de Jupiter, planetas orbitando estrellas desoladas, el Centro Galactico parpadeando en la oscuridad.
Todos estos momentos se perderan en el tiempo, como lagrimas en la lluvia.
Es tiempo de morir.

Cariños,
Antu por NACO

Figure 6. This email was sent by the support astronomers after NaCo's last night of operation. It shows what NaCo means for most of us: lots of emotions, lots of memories, and wonderful people working together.

The final years

In 2013, NaCo was supposed to be decommissioned. However, an important astronomical event was on the horizon — the close encounter of the star S2 with the black hole in the centre of our Galaxy. As mentioned above, since the beginning of its operation NaCo played a key role in monitoring the motions of stars close to our Galactic centre. Now in 2018, one of these stars, S2, which has a highly elliptical orbit, was supposed to get so close to the black hole that the extreme gravity would make the effects of general relativity detectable. For this event, new instruments like GRAVITY were created, but an instrument was needed to actually follow the star and determine the precise orbit before and after the encounter. So, in 2014 NaCo was brought back to life, this time installed on the Nasmyth A focus of UT1. Consternation arose when it became clear that the CONICA detector couldn't be brought back to life. Luckily, ISAAC had been decommissioned a few years before and had also been equipped with an Aladdin detector. So the old ISAAC detector was refurbished and put into NaCo. Some long and frustrating re-commissioning runs were needed to get everything up and running. NaCo's facilities were drastically reduced — no more spectroscopy and everything had to be done in service mode, since Paranal did not have sufficient engineering resources to keep all the modes up and running.

Apart from the regular Galactic centre observations, another main science driver was the imaging of planets with the new AGPM mask, and the reduced NaCo was of course also offered in open time to the community. In 2018, after a major problem with the detector controler, the visible wavefront sensor had to be decommissioned. At that time, NaCo required several hours attention to be operational at night and may have become the most cursed instrument on Paranal but, when working, it delivered spectacular images; the monitoring and astrometry of the Galactic centre was a great success
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(GRAVITY Collaboration et al., 2018) and even in its old age NaCo was still contributing to exciting science results. At the moment of writing, 699 papers have been published using NaCo data[3].

NaCo's last night of operation, 1 October 2019, was cloudy, so a planned last-light image of Io could not be taken. Last light was instead recorded from the standard star HD590 at 04:22:50 UT on 30 September 2019. After that last night of operation, a very emotional email was sent by the night crew to all colleagues in Paranal (see Figure 6), expressing the emotions that we all felt when NaCo was finally switched off.

Beyond NaCo

NaCo leaves a legacy of amazing data that are available in the archive. The pipeline will be kept alive and updated with system changes in order to ensure the ongoing use of these data. A history of NaCo, in particular a list of events that might influence which calibrations to take for which epoch of observations is available on NaCo's webpage[4].

Of course, NaCo is not the end by any means. AO continues to evolve, new generations of AO instruments like the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE), the Multi Unit Spectroscopic Explorer (MUSE) and the Enhanced Resolution Imager and Spectrograph (ERIS) are being operated at Paranal or will be coming soon. AO techniques will be key for any instrument on the ELT in future. All of these operational modes were originally tested on NaCo. We are continuously improving these techniques but, to quote a former Instrument Scientist, "NaCo was instrumental in making adaptive optics mainstream".

Acknowledgements

We acknowledge the extensive use of ESO press releases, ESO newsletters and ESO images. Many people have contributed to making NaCo observations possible. We would like to thank the engineers and scientists who built the instrument, and those who developed and installed new modes at later stages, the various commissioning teams, the hardware and software engineers who kept this delicate instrument in good shape, the colleagues in Garching working on instrumental upgrades, pipeline development, quality control and user support, all the members of the Instrument Operation Team over the time, and all the support astronomers and telescope operators using NaCo at UT1 or UT4. Last but not least, we would like to thank the astronomical community for their interest and for using NaCo to advance their fascinating science cases.

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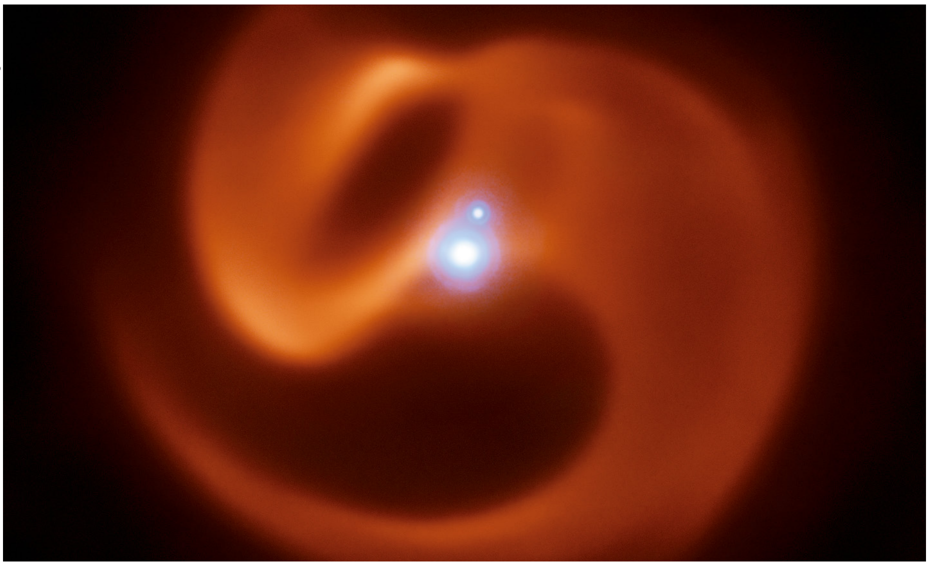
Links

[1] ESO Press Release 0204 showing NaCo image of Saturn's rings: http://www.eso.org/public/news/eso0204
[2] NASA Deep Impact mission: https://www.jpl.nasa.gov/missions/deep-impact/
[3] Publications with NaCo: http://telbib.eso.org/?-boolany=or&boolaut=or&boolti=or&year-to=2020&instrument%5B%5D=naco&boolins=or&-booltel=or&search=Search
[4] NaCo's history: www.eso.org/sci/facilities/paranal/decommissioned/naco/History.html

Notes

[a] The French consortium consisted of Office National d'Etudes et de Recherches Aérospatiales (ONERA), Laboratoire d'Astrophysique de Grenoble (LAOG) and Observatoire de Paris (DESPA and DASGAL). The Project Manager was Gérard Rousset (ONERA), the Instrument Responsible was François Lacombe (Observatoire de Paris) and the Project Scientist was Anne-Marie Lagrange (Laboratoire d'Astrophysique de Grenoble). It was supported by the Institut National des Sciences de l'Univers (INSU) of the Centre National de la Recherche Scientifique (CNRS).
[b] The German Consortium included the Max-Planck-Institut für Astronomie (MPIA) (Heidelberg) and the Max-Planck-Institut für Extraterrestrische Physik (MPE) (Garching). The Principal Investigator (PI) was Rainer Lenzen (MPIA), with Reiner Hofmann (MPE) as Co-Investigator.



The VISIR instrument on ESO's VLT captured this stunning image of a newly-discovered massive binary star system. Nicknamed Apep after an ancient Egyptian deity, it could be the first gamma-ray burst progenitor to be found in our galaxy. The triple star system was captured by the NACOadaptive optics instrument on the VLT.

This artist's impression shows the exiled asteroid 2004 EW_{95}, the first carbon-rich asteroid confirmed to exist in the Kuiper Belt and a relic of the primordial Solar System. This curious object likely formed in the asteroid belt between Mars and Jupiter and must have been transported billions of kilometres from its origin to its current home in the Kuiper Belt.

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SPHERE Unveils the True Face of the Largest Main Belt Asteroids

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Over the past 2.5 years, we have been carrying out disc-resolved observations of a substantial fraction of all large (*D* > 100 km) main-belt asteroids, monitoring them at high angular resolution throughout their rotation, and sampling the main compositional classes, using the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument on the VLT. These observations enable us to characterise the internal structure of our targets from their density as well as their cratering record down to ~ 30 km in diameter. Such information, in turn, places unprecedented constraints on models of the formation of the Solar System and the collisional evolution of the main belt.

Scientific context

Asteroids are minor planets ranging in size from a few metres to a few hundred kilometres which are located between Mars and Jupiter (typically between 2 and 3.3 astronomical units [au]). The diversity in their surface composition (for example, metallic iron, basalt, mixtures of silicates such as olivine and pyroxene, water-rich silicates, water ice) — as inferred from spectroscopic observations — and their orbital distribution across the main belt (see, for example, Vernazza & Beck, 2017 for a review) have provided unique constraints to Solar System formation models which could not have been derived from observations of the giant or telluric planets themselves.

It is now understood that the present-day asteroid belt hosts bodies that were formed at large heliocentric distances (> 10 au) as well as bodies that may have formed close to the Sun (< 1.5 au) and that they have ended up at their current location following giant planet migration (see, for example, the Nice and Grand Tack models; Levison et al., 2009; Walsh et al., 2011) as well as gravitational interaction with the embryos of the telluric planets (Bottke et al., 2006). Broadly speaking, the idea that the asteroid belt is a condensed sample of the primordial Solar System has gradually emerged.

Whereas our understanding of the surface composition of asteroids and its distribution across the asteroid belt has improved enormously over the last decade, see recent reviews by Burbine (2014) and Vernazza & Beck (2017) the same cannot be said regarding their internal structure, which is best characterised by their density. To constrain the density, one needs to fully reconstruct the 3D shape of a body, to estimate its volume and to determine its mass from its gravitational interaction with other asteroids, preferably (whenever possible) with its own satellite(s).

This is due to the fact that disc-resolved observations of asteroids — contrary to disc-integrated observations of these same bodies (from light curves and/or visible and infrared spectroscopy) — have so far been obtained with sufficient spatial resolution for only a few bodies, either from dedicated interplanetary missions (for example, Galileo, Near Earth Asteroid Rendezvous (NEAR), Rosetta, Dawn, Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer [OSIRIS-Rex], Hayabusa 1 & 2) or from remote imaging with the Hubble Space Telescope (HST) and adaptive-optics-equipped ground-based telescopes (for example, the VLT and the Keck Observatory) in the case of the largest bodies.

The drastic increase in angular resolution (by about a factor of three) with respect to the HST that is possible with the new generation of adaptive optics using the Zurich imaging polarimeter (ZIMPOL) on SPHERE indicates that the largest main-belt asteroids become resolvable worlds and are thus no longer extended point sources. To place this in context, these asteroids have diameters greater than 100 km and angular sizes typically greater than 100 milliarcseconds (mas). With the SPHERE instrument, craters with diameters greater than approximately 30 km can now be identified on the surfaces of main-belt asteroids and the shapes of the largest asteroids can be accurately reconstructed (for example, Marsset et al., 2017).

To maximise the science return of the SPHERE instrument in the field of asteroid studies, we proposed an ESO Large Programme with the aim of characterising the shape, density, internal and compositional structure, and surface topography of a statistically significant fraction of *D* > 100-kilometre main-belt asteroids (~ 35 out of ~ 200 asteroids). Our sample covers the major compositional classes (S, B/C, Ch/Cgh, X, P/D; DeMeo et al., 2009; DeMeo & Carry, 2013). The survey started in April 2017 and ended successfully in September 2019.

Methods

To achieve our science objectives, we image our targets with SPHERE/ZIMPOL throughout their rotation (we collect images every ~ 60 degrees in planetocentric longitude). These images are subsequently reduced and deconvolved with the MISTRAL algorithm (Fusco et al., 2003; Mugnier, Conan & Fusco, 2004) using a point spread function (PSF).
At the beginning of our observing programme, we were observing a stellar PSF either before or just after every asteroid observation. However, because the

deconvolution with the stellar PSF did not produce systematically satisfactory results, we investigated alternative methods to increase the sharpness of the image. We noticed that in several cases we achieved a better result by using stellar PSFs acquired on different nights. We therefore tested the deconvolution process with synthetic PSFs modeled by a 2D Moffat function. The deconvolution using a Moffat PSF always converged towards an acceptable solution by varying the Moffat parameters (Fétick et al., 2019). We therefore started systematically using a parametric PSF to deconvolve our images (for example, Viikinkoski et al., 2018; Fétick et al., 2019). Notably, the case of Vesta (Figure 1) has confirmed the accuracy of our image deconvolution algorithm. Nevertheless, it is clear that our programme provides a strong motivation for further development of deconvolution algorithms in order to limit artefacts with additional priors, incorporate non-axisymmetric features of the stellar PSF, and improve convergence and stability.

The deconvolved images serve as input to a 3D shape reconstruction algorithm (ADAM; Viikinkoski, Kaasalainen & Durech, 2015 or MPCD; Jorda et al., 2016). Even though we already have low-resolution, convex, shape models from existing light curves for all our targets, the SPHERE data allow us to drastically improve those models by producing more realistic non-convex shape models, revealing the topography of individual craters ($D \geq 30$ km). Thus, thanks to SPHERE's unique angular resolution, we have been able to open an entirely new window on asteroid exploration. Cratering records that are now available for our targets allow us to address their global geology, as in the case of (7) Iris for instance (Hanus et al., 2019).

The methods we employ to derive the physical properties of our targets have been validated in the case of the asteroid (21) Lutetia (Carry et al., 2010, 2012), which is a relatively small object ($D \sim 98$ km) compared to our targets. The asteroid was visited by the ESA Rosetta mission in 2010 (Sierks et al., 2011). With our methods, the inferred spin coordinates were accurate to one degree and the absolute dimensions to within 2 km with respect to those derived from the Rosetta fly-by data.

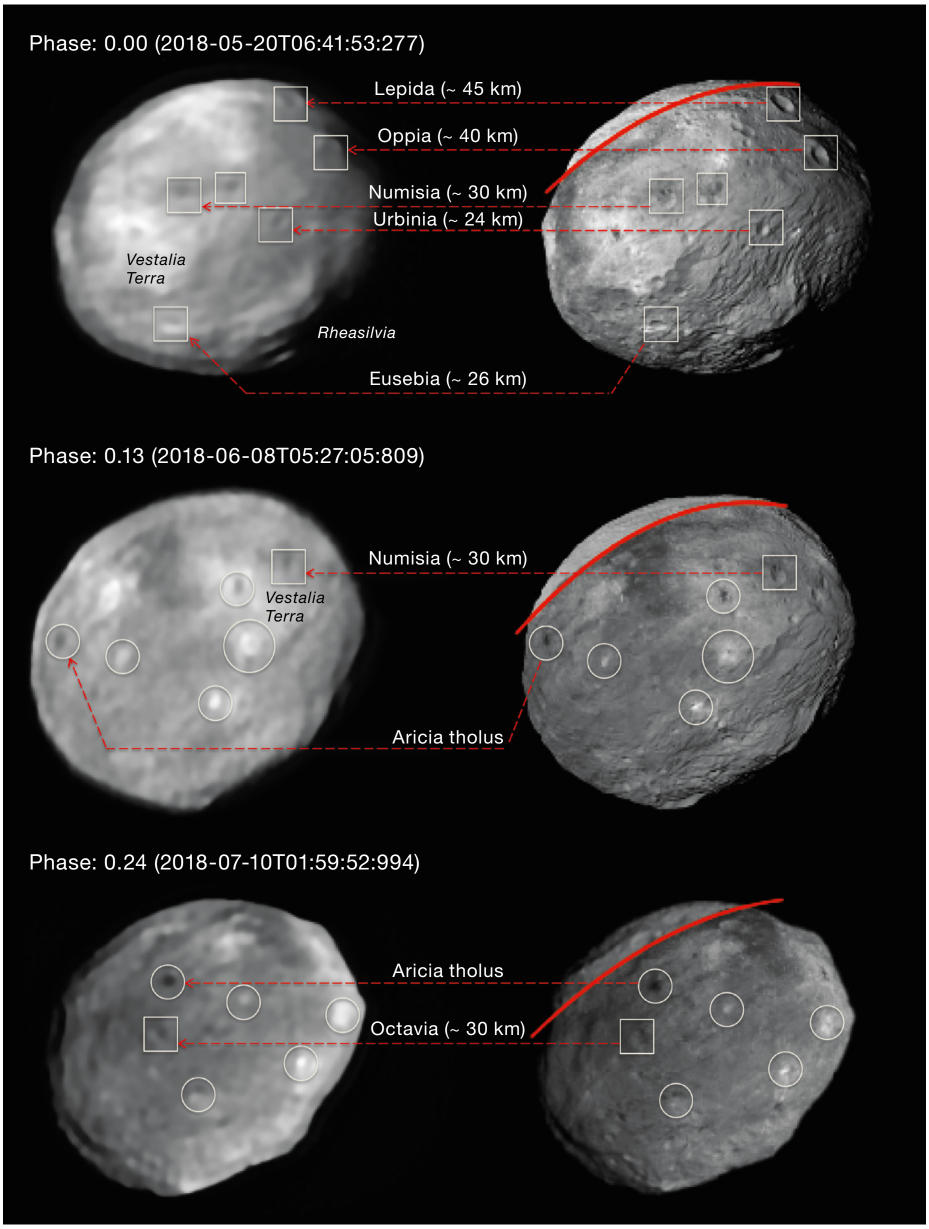

Figure 1. Comparison of the VLT/SPHERE deconvolved images of Vesta (left column) with synthetic projections of the Dawn model produced with OASIS and with albedo information (right column). The main structures that can be identified in both the SPHERE images and the synthetic ones are highlighted: craters are outlined by squares and albedo features by circles. Reproduced from Fétick et al., 2019.

Hereafter, we summarise some of the main results obtained so far. These results illustrate well the diversity of the science questions that can be investigated via such an imaging survey.

A bluffing view of (4) Vesta

With a mean diameter of 525 km (Russell et al., 2013), (4) Vesta is the second largest body in the asteroid belt. In the early 1990s, telescopic observations of small asteroids on similar orbits revealed the presence of numerous bodies with spectral properties similar to those of Vesta (Binzel & Xu, 1993). It was understood that these bodies originated as fragments from Vesta that had been excavated in one or more giant impacts. A few years later, observations performed with the HST revealed the presence of an impact crater 460 km in diameter near the south pole of Vesta (Thomas et al., 1997), thus confirming the collisional origin of the Vesta-like bodies. Later on, the NASA Dawn mission characterised the surface topography of Vesta in detail, revealing the existence of two overlapping basins in the south polar region and a central peak whose height rivals that of Olympus Mons on Mars (for example, Russell et al., 2012; Jaumann et al., 2012; Marchi et al., 2012; Schenk et al., 2012).

Our SPHERE images have recovered the surface of Vesta in great detail (Figure 1; Fétick et al., 2019). Most of the main topographic features present across Vesta's surface can be readily recognised from the ground. These include the south pole impact basin and its prominent central peak, several $D \geq 25$ kilometre-sized craters and also Matronalia Rupes, including its steep scarp and its small and big arcs. On the basis of our observations, it follows that next-generation telescopes with mirror sizes in the range 30–40 m (for example, ESO's ELT) should in principle be able to resolve the remaining major topographic features of (4) Vesta (i.e., equatorial troughs, north-south crater dichotomy), provided that they operate at the diffraction limit in the visible.

A bright future for asteroid family studies

Our SPHERE observations of asteroid (89) Julia (Vernazza et al., 2018; Figure 2), a $D \sim 140$ km S-type asteroid and the parent body of a small collisional family that consists of 66 known members with $D < 2.5$ km, have revealed the presence of an impact crater (~ 75 km wide) that could be the origin of this family. In addition, we studied both the impact event by means of smoothed particular hydrodynamic simulations and the subsequent long-term orbital evolution of the asteroid family, to determine its age (30–120 Myr). It follows that the same type of science investigation that could be performed 20 years ago with the HST in the case of (4) Vesta and the discovery of its south pole impact basin at the origin of the Vesta family (Thomas et al., 1997) can now be performed for many $D > 100$ km main-belt asteroids with VLT/SPHERE. In the field of asteroid-family studies, the future will only get brighter with the resolving power of the extremely large telescopes (ESO's ELT, the Thirty Meter Telescope [TMT], and the Giant Magellan Telescope [GMT]). All-sky surveys using the Vera C. Rubin Observatory will surely discover many new small families. The follow-up with adaptive optics observations of their parent bodies may allow us to reconstruct the respective impact craters at the origin of these families.

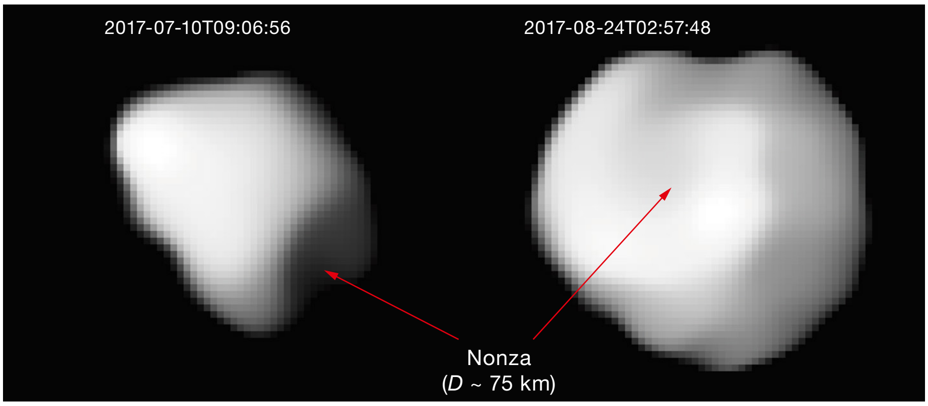

Figure 2. SPHERE/ZIMPOL images of (89) Julia deconvolved with the MISTRAL algorithm. Nonza, the likely impact crater at the origin of a small collisional family, is highlighted.

At the same time, such investigations may help to establish new meteorite-asteroid connections. Indeed, asteroid families likely constitute a major source of meteorites. The case of Vesta supports such a hypothesis, it being likely that the howardite-eucrite-diogenite (HED) meteorites — achondrite meteorites which account for about 6% of falls — are derived from its family. In the near future, it will therefore become possible to search for the origin locations of individual meteorite falls using their cosmic ray exposure ages — which indicate the time they have been traveling in space since being excavated from their parent body — in conjunction with the estimated asteroid family ages and high-angular-resolution imaging observations of the presumed parent bodies.

Asteroids with satellites

Multiple-asteroid systems (binaries, triples) are important because they represent a sizable fraction of the asteroid population and because they enable investigations of properties and processes that are often difficult to probe by other means. In particular, Earth-based observations of binaries and triples provide the most powerful way of deriving precise masses and thus densities for a substantial number of objects (for example, Descamps et al., 2011; Marchis et al., 2013). The only other way to constrain asteroid masses with similar precision is with dedicated interplanetary missions, either a fly-by for the largest ones (as in the case of (21) Lutetia) or a rendezvous (for example, the Dawn mission, OSIRIS-Rex and Hayabusa 1 & 2).

Direct imaging performed in the course of our Large Programme is a very efficient way of discovering new moons, constraining their orbital parameters and hence the total mass of the system (primary + secondary). In the case of a small secondary (which is always the case for our targets), the total mass is dominated by the primary, implying that the mass of the primary can be well constrained (usually with < 10% uncertainty).

Our programme has allowed us to discover a moon around the C-type asteroid (31) Euphrosyne (Vernazza et al., 2019). With an estimated diameter of ~ 270 km, Euphrosyne is so far the largest known main-belt asteroid with a companion. We have also investigated the compositional structure of the binary asteroid (41) Daphne (Carry et al., 2019; Figure 3). Our observations imply a density similar to that of CM chondrites, and thus a homogeneous internal structure for that object, in agreement with numerical models simulating the early thermal evolution of the parent bodies of CM chondrites.

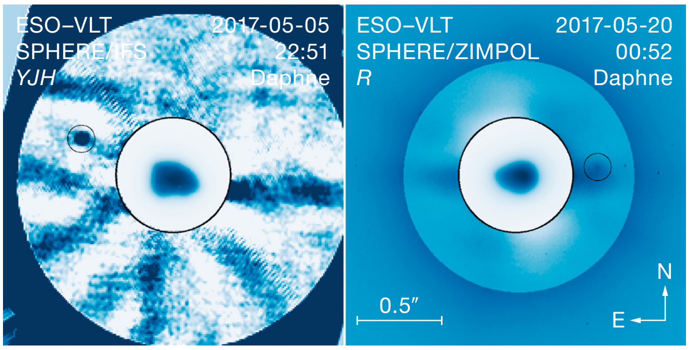

Figure 3. Images of (41) Daphne and its satellite. Daphne's image is displayed in the inner circle and the outer region shows the satellite after halo removal (highlighted by a small circle). Reproduced from Carry et al. (2019).

Perspectives

New opportunities for ground-based asteroid exploration, namely geophysical and geological studies, are becoming available thanks to SPHERE's unique capabilities. Also, the present work represents the beginning of a new era of asteroid-family studies. Notably, our SPHERE observations using the VLT have demonstrated in a striking manner how the gap between interplanetary missions and ground-based observations is getting narrower (Fétick et al., 2019). With the advent of extremely large telescopes (ESO's ELT, GMT, TMT), the science objectives of future interplanetary missions will have to be carefully thought out so that these missions will complement, rather than duplicate, what will be achieved via Earth-based telescopic observations. For instance, future ELT adaptive-optics imaging of main-belt asteroids will allow us to resolve craters down to ~ 2–5 km in size implying that we shall be able to characterise their global geological history from the ground. Consequently, missions performing cosmochemistry experiments, landing and eventually returning a sample, should be preferred at the forefront of *in-situ* exploration.

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Paranal Observatory at sunset.

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The ASPECS Survey: An ALMA Large Programme Targeting the Hubble Ultra-Deep Field

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The ALMA Large Programme ASPECS (The ALMA SPECtroscopic Survey in the UDF) set out to measure the dust and molecular gas content in distant galaxies in the best-studied cosmological deep field, the Hubble Ultra-Deep Field (UDF). Thanks to a unique observing technique, the survey resulted in a full census of gas-rich galaxies in the UDF, yielding dozens of detections in dust continuum and molecular gas emission. Their physical properties could be accurately constrained thanks to the unparalleled wealth of ancillary data, including the most sensitive Hubble Space Telescope (HST) and VLT/MUSE observations. The data confirm that, on average, the gas mass fractions of distant galaxies decreased by an order of magnitude since redshift 2, and that the gas depletion times are ~ 1 Gyr, in approximate agreement with the local value. The ASPECS deep Band 6 continuum map of the field shows that more than 90% of the dust continuum emission in the field has been resolved in individual galaxies. The total CO emission in this well defined cosmological volume is used to constrain the evolution of the cosmic molecular gas density. Together with previous measurements of the evolution of the cosmic densities of stellar mass, star formation rate and atomic gas, these measurements provide quantitative constraints of the gas accretion rate onto the central discs of galaxies.

ASPECS motivation and survey strategy

It has been well established that stars form from molecular gas. In order to characterise the evolution of galaxies through cosmic time, a measurement of their molecular gas content, and its evolution over cosmic time, is therefore indispensable. Such a measurement was one of the three prime directives driving the ALMA project from its conception. With this goal in mind, the ALMA Large Programme ASPECS, the first extragalactic large programme approved for ALMA, was designed to make an unbiased, three-dimensional survey of the molecular gas content of galaxies in the best studied extragalactic deep field, the iconic Hubble Ultra-Deep Field (UDF).

Choice of field

Choosing the UDF as the prime target for this survey (Figure 1) was straightforward. The UDF has the highest quality of observations in depth and resolution across the electromagnetic spectrum, extending beyond traditional continuum imaging, and is ideally situated for ALMA observations. Any additional observations, for example, under ASPECS but also other ALMA initiatives, add to the legacy value of this deep field. Besides ASPECS, recent key observations of the field include major Guaranteed Time Observation (GTO) initiatives with the Multi Unit Spectroscopic Explorer (MUSE) on ESO's VLT — the most sophisticated wide-field optical integral field unit available (Bacon et al., 2017). The availability of the MUSE data, from which over a thousand spectroscopic redshifts have been derived, enables significant gains in line stacking in 3D space. Furthermore, the UDF has also been selected as the primary deep field for James Webb Space Telescope (JWST) guaranteed time programmes, and observations are expected early in JWST's mission (at the end of 2021). In summary, the UDF will maintain its status as the state-of-the-art deep survey field for the foreseeable future.

Observational strategy

The observational approach of ASPECS to studying the molecular gas and dust in distant galaxies is unique as it does not preselect galaxies from other multiwavelength data (for example, through measurements of their stellar mass or star formation rate). Instead, imaging a significant region on the sky with ALMA mosaics, as well as scanning in frequency space, yields an unbiased measurement of molecular gas in a well defined cosmic volume. This is due to the fact that the key tracer of molecular gas, the carbon monoxide molecule (CO), emits radiation at distinct frequencies that approximately correspond to multiples of the frequency of the CO(1–0) ground transition at 115 GHz (corresponding to a wavelength of ~ 2.7 mm). These emission lines are then redshifted by the change in the cosmic scale factor for distant sources (Figure 2). For example, the CO(3–2) line at ~ 345 GHz will be redshifted to an observed frequency of ~ 100 GHz for a galaxy at redshift $z = 2.5$.

The net observational results of the ASPECS observations are 3D data cubes, the three axes being right ascension, declination and frequency, where frequency equates to the line-of-sight distance via the redshift. The areal coverage of the ASPECS observations is shown in Figure 1, and the frequency coverage in Figure 2. ASPECS covers two frequency regimes, the 3-mm band and the 1-mm band. This approach was chosen so as to maximise the cosmic volume for redshifted CO lines, as well as to obtain millimetre continuum images of the UDF to unprecedented depths.

Data products

The primary data products of the ASPECS observations are the Band 3 and Band 6 data cubes. In Figure 3 we show 2D renderings of the 3D cubes. Spectral lines of individual galaxies show up as point sources in the 3D cubes, corresponding to CO emission from a galaxy at a given position and redshift. In the 1-mm cube some linear features in frequency are also apparent: these features arise from dust continuum emission from the highest star formation rate galaxies in the field. Consequently, these spectral scans also deliver the deepest-ever dust continuum maps of the Universe. Taken together, these methods enable a full characterisation of the molecular gas and dust in the cosmological volume probed by the UDF, down to galaxy masses that encompass the bulk of the luminosity and mass out to redshifts ~ 4, when the Universe was only 1.6 billion years old, i.e., 1/8th of today's age.

The validity of the observational approach for the ASPECS Large Programme was demonstrated by a number of pilot programmes, both with the IRAM (Institut de Radio Astronomie Millimétrique) Plateau de Bure Interferometer (now called NOEMA; Walter et al., 2014; Decarli et al., 2014) and ALMA observations in earlier cycles (Walter et al., 2016; Aravena et al., 2016a,b; Decarli et al., 2016a,b; Bouwens et al., 2016; Carilli et al., 2016). Our frequency scans of a contiguous deep field are complementary to targeted studies of high-redshift galaxies, most notably under the IRAM Plateau de Bure HIgh-*z* Blue Sequence Survey projects (PHIBSS1/2; Tacconi et al., 2010, 2013, 2018; Genzel et al., 2015).

The evolution of dust and molecular gas in the UDF

One of the core results of ASPECS is to pinpoint which of the many hundreds of galaxies visible in the HST observations of the UDF are rich in molecular gas and dust, i.e., the material that is essential for star formation to proceed. The ASPECS survey (including its pilot programme) is reaching completion, and will eventually result in a total of 17 publications in international refereed journals[1]. We highlight some of the key results here.

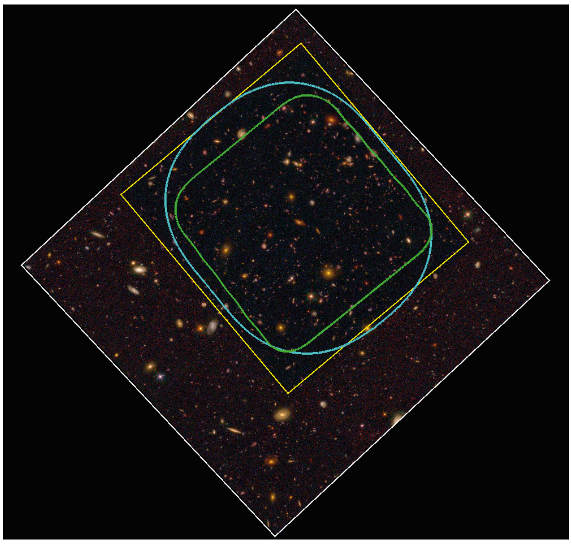

Figure 1. Spatial coverage of ASPECS within the Hubble Ultra-Deep Field (UDF) in Band 3 (region indicated in blue) and Band 6 (in green). A 17-pointing mosaic was needed for the Band 3 observations, and 85 pointings were used for the Band 6 observations. The deepest part of the UDF, also referred to the XDF, is shown in yellow. The colours represent a multi-band HST image.

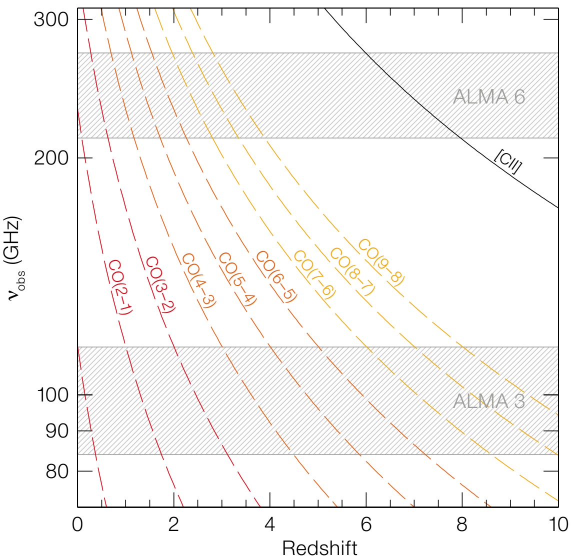

Figure 2. Frequency coverage of the ALMA Bands 3 and 6 with ASPECS (grey regions). Five separate tunings were required to cover the full ALMA Band 3 and eight tunings were needed for Band 6. The different bands cover the different rotational transitions of CO as a function of redshift, as indicated by the coloured dashed lines. The [CII] line is also covered for galaxies at redshift $6 < z < 8$ in Band 6. The data can also be used to construct continuum maps in Band 3 and 6. Figure taken from Walter et al. (2016).

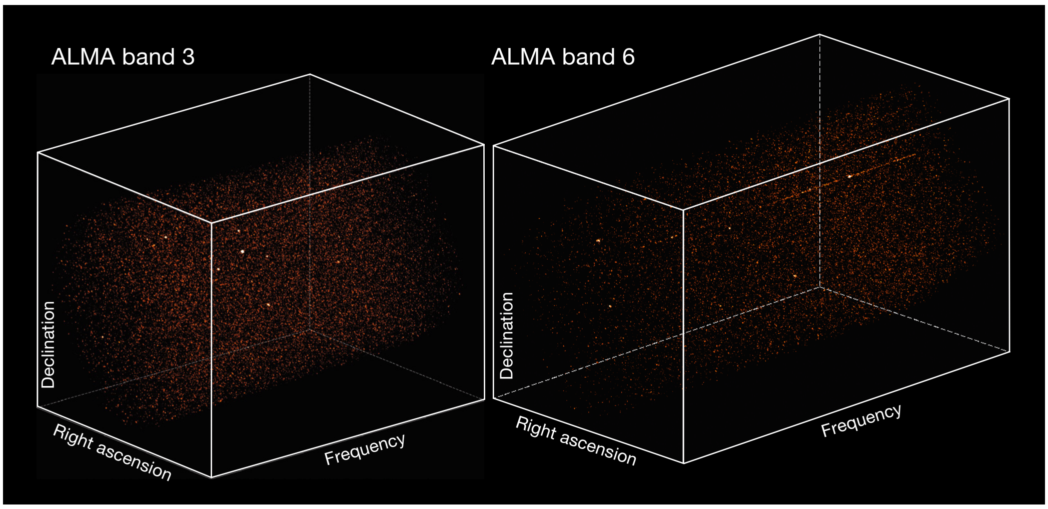

Figure 3. ASPECS delivers two 3D data cubes, one for Band 3 and one for Band 6, with the following axes: right ascension, declination, and frequency. These figures show 2D renderings of the cubes. Individual line detections of galaxies in the UDF are clearly visible in the data cube. In most cases these correspond to emission from rotational transitions of carbon monoxide. Linear features (most prominently seen in the Band 6 observations) correspond to continuum detections.

Continuum observations

The unprecedented depth of the ALMA 1-mm continuum map of < 10 μJy (shown in Figure 4) obtained by ASPECS over the UDF region puts critical constraints on the abundance of dust reservoirs in the early Universe. Gonzalez-López et al. (2020) report the detection of 32 unambiguous dusty galaxies. The cumulative number of sources reveals a dearth of dusty galaxies at decreasing 1-mm flux densities compared to extrapolations from previous surveys. A direct consequence of this result is that deeper observations will not yield many more new dusty galaxies, i.e., any future, deeper observations at these wavelengths will not substantially alter the budget of dust emission in the UDF as unveiled by ASPECS. Thus, ASPECS was able to pinpoint as individual galaxies the population responsible for almost all of the Extragalactic Background Light (EBL) at 1 mm in the UDF.

The comparison of 1-mm dust continuum number counts shown in Figure 5 with models (Popping et al., 2020) shows excellent agreement between model and data, even when splitting the sample into bins of basic galaxy properties (redshift, stellar and dust masses, star formation rate [SFR]). These number counts are dominated by galaxies in the redshift range $1 < z < 3$, and show a lack of dust reservoirs for less massive galaxies. The absence of major dust reservoirs in low-mass galaxies implies that dust obscuration is unlikely to be a major concern for the many low-mass (dwarf) galaxies seen in the UDF, with important implications for calculating the evolution of cosmic star formation rate density from rest-frame ultraviolet observations out to the highest redshifts (Bouwens et al., 2016; in preparation).

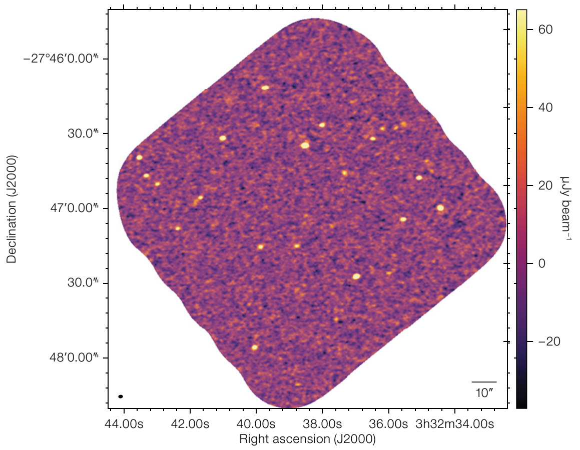

Figure 4. ASPECS Band 6 continuum map of the UDF (Gonzalez-López et al., 2020). The noise reached in this map is ~ 9.5 μJy/beam, making this the deepest ALMA continuum map of a cosmological deep field obtained to date. There are 32 unambiguously detected dusty galaxies in the field.

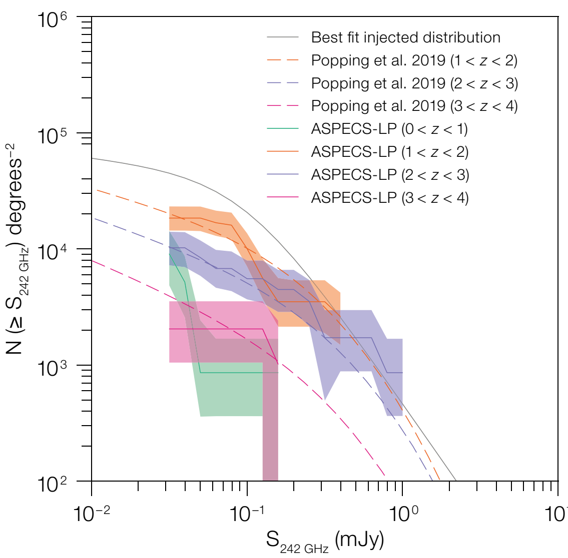

Figure 5. The solid grey line shows the ASPECS 1-mm continuum number counts recovered in the Band 6 continuum map. The coloured solid lines show the number counts as a function of redshift. The dashed lines are from the theoretical models by Popping et al. (2020). There is good agreement between the models and the observations. Most of the galaxies that are detected in dust continuum in the UDF are located at redshifts $1 < z < 3$. Figure taken from Gonzalez-López et al. (2020).

Gas-mass selected galaxies in the UDF

The most significant ASPECS CO detections in the UDF are shown in Figure 6, both as CO spectra and as contours on top of the HST multi-band imaging. It is clearly evident from Figure 6 that the gas-selected galaxy sample uncovered by ASPECS consists of galaxies of different types and environments.

Aside from just pinpointing the galaxies that contain most of the cold dust reservoirs in the UDF, the wealth of multi-wavelength data available for the ASPECS/UDF field, which includes deep HST imaging and MUSE spectroscopy, enables a full characterisation of the physical properties of the ASPECS galaxies. We find that almost all CO emitters have 1-mm dust detections, indicating an obvious connection between molecular gas and dust, yet with varying interstellar medium properties. Interestingly, most ASPECS galaxies appear relatively bright in the HST optical/near-infrared images ($m_{F160W} < 25$ magnitudes), suggesting less obscuration than that observed in prototypical massive, dusty star-forming galaxies ("submillimetre galaxies"), and implying a lack of "optically/near-infrared dark" galaxies within the ASPECS sample.

Many of the ASPECS galaxies are found to be on the so-called galaxy main-sequence (for example, Brinchmann et al., 2004; Elbaz et al., 2007), but others are classified as starbursts or quiescent galaxies. A significant number of galaxies are found in crowded regions, the result of either the presence of companions, or chance superpositions. The deep optical spectroscopy from VLT/MUSE (hundreds of galaxy spectra in the UDF; Inami et al., 2017), has been used, in some cases, to unambiguously constrain the CO transition and hence the redshift of a galaxy (Boogaard et al., 2019). In most of the ALMA-detected galaxies more than one rotational transition of the CO molecule is detected. These multi-line observations are used to put first constraints on the physical properties of the interstellar medium (for example, density,

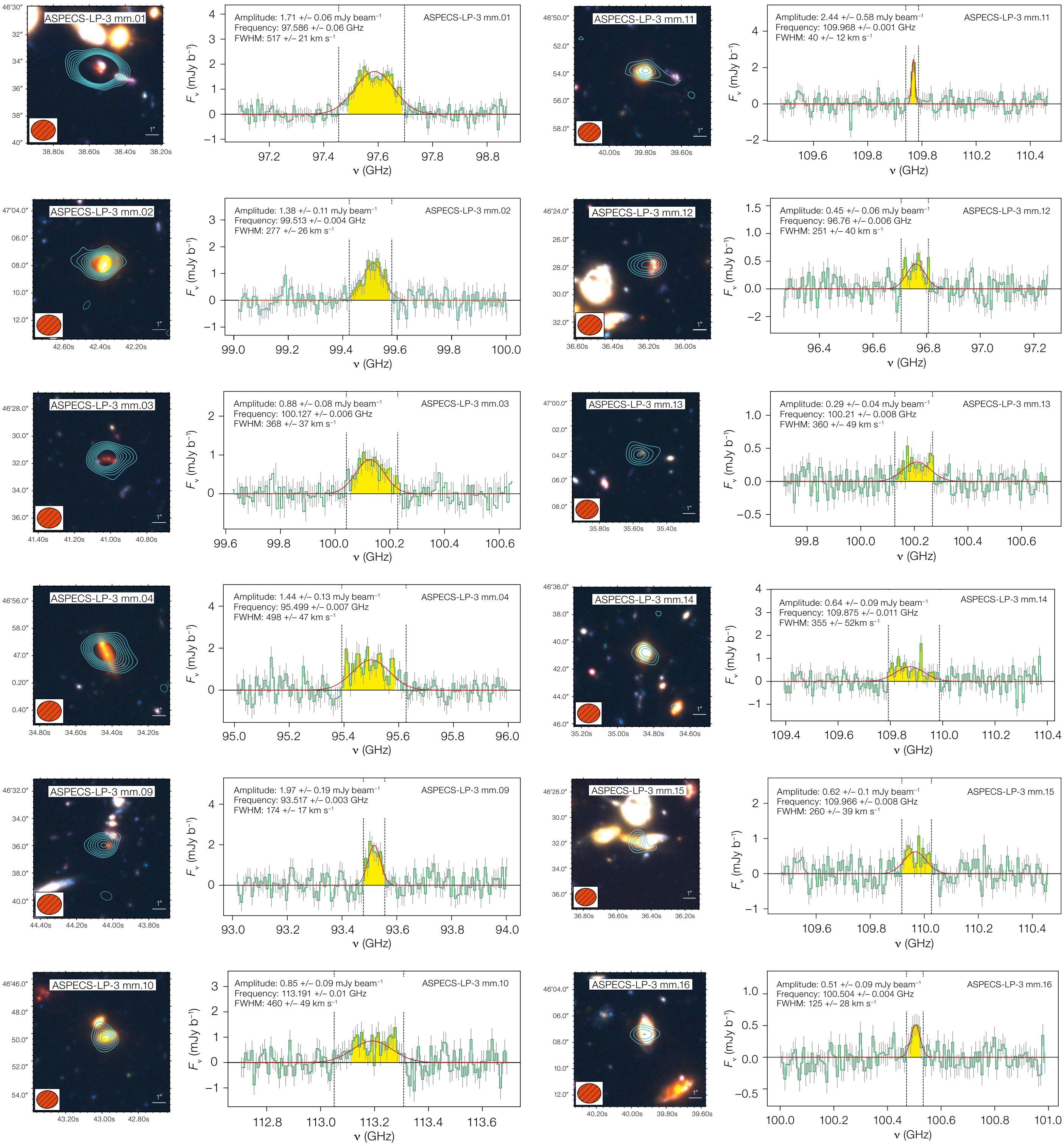

Figure 6. Collection of detected CO lines (spectra) and the corresponding CO emission overplotted as contours on the HST multi-band images of the UDF. Our dust/gas-selected sample of galaxies in the UDF covers a large variety of galaxies in different environments. Figure taken from Gonzalez-López et al. (2019).

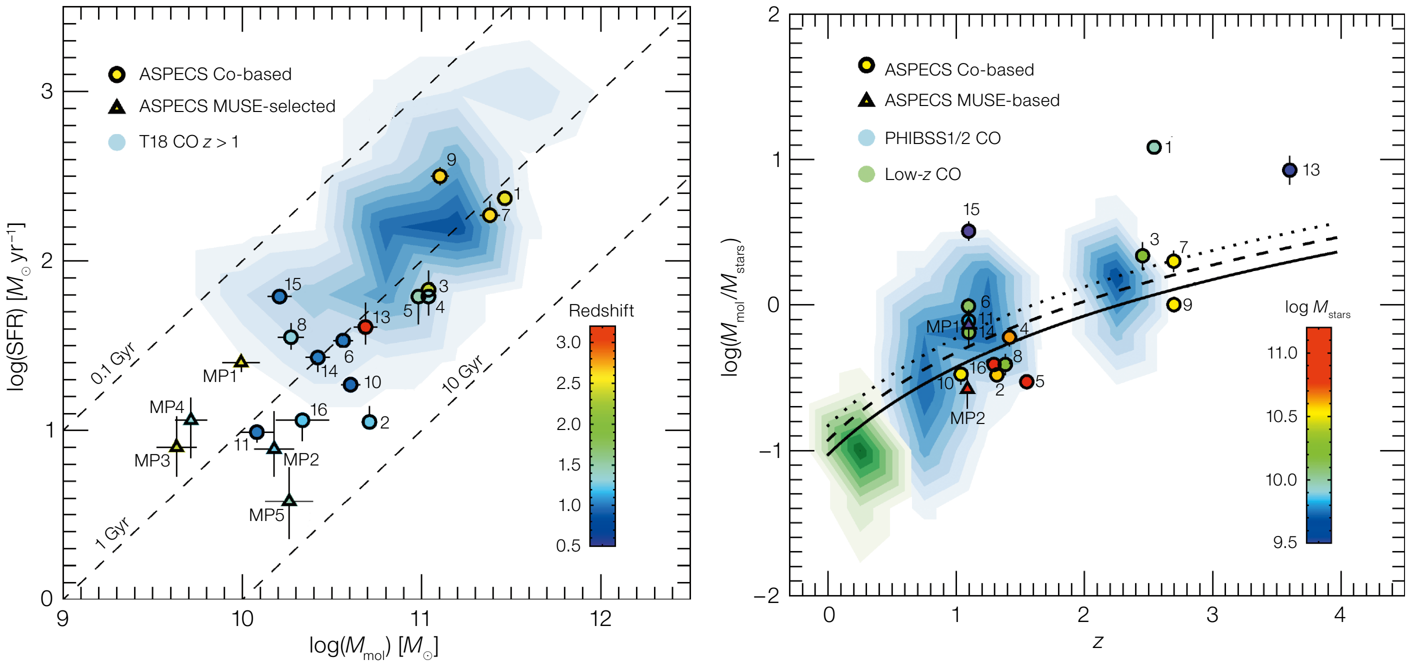

Figure 7. Left: Star formation rate (SFR) vs. molecular gas content of the galaxies in the UDF — the ASPECS CO detections are indicated as coloured symbols. The blue-shaded area is from the CO measurements obtained by the PHIBSS1/2 surveys (Tacconi et al. 2013; 2018). Overall, the gas-selected galaxies in the UDF show properties similar to those of galaxies in previous, targeted studies. The gas depletion times, defined as M_{mol}/SFR, are shown as dashed lines. Values are typically ~ 1 Gyr, irrespective of redshift, similar to what is found in the local universe. Right: Gas mass fraction, defined as M_{mol}/M_{stars}, as a function of redshift. The gas-selected galaxies in the UDF again show behaviour similar to that found in previous, targeted studies, albeit with significant scatter. Overall the gas mass fraction decreases by about an order of magnitude from redshift 2 to today's Universe. Figures taken from Aravena et al. (2019).

temperature). In addition to CO, atomic carbon (CI) is also detected in many sources (Boogaard et al., in preparation). Together with the dust continuum emission, these data provide a number of different ways of estimating molecular gas masses, corresponding to the fuel for star formation in galaxies (Aravena et al., 2020).

In Figure 7 we present some of the properties of the ASPECS-selected galaxies in context with other studies. In the left panel of Figure 7 we plot the star formation rate (SFR) of a galaxy as a function of gas mass (M_{mol}). In such a plot, diagonal lines (indicated as dashed lines) are lines of constant gas depletion time. The gas-mass selected ASPECS galaxies in the UDF cover a similar parameter space as do earlier targeted studies (Tacconi et al., 2013, 2018), albeit with a somewhat larger scatter. On average, their depletion time is ~ 1 Gyr irrespective of redshift, which is similar to the value derived for star-forming galaxies in the local Universe. In the right panel of Figure 7 the gas mass fraction, defined as M_{mol}/M_{stars}, is plotted as a function of lookback time. Our gas-selected galaxy sample confirms the conclusion based on targeted samples, that there is a fundamental change in the properties of star forming galaxy over time, namely, that the gas mass fraction decreases by an order of magnitude from redshifts z ~ 2 to today (Aravena et al., 2019).

The cosmic evolution of the molecular gas density

The CO emission in the data cubes can be used to derive CO luminosity functions for the different CO transitions (i.e., redshifts) covered by ASPECS. By assuming empirical relations for the CO excitation in galaxies, the expected emission in the rotational ground transition of CO(1–0) can be derived. From that, a molecular gas mass can be assigned to a galaxy by employing the so-called CO-to-H_2 conversion factor (Bolatto, Wolfire & Leroy, 2013). This conversion factor is known to be metallicity-dependent. Fortunately, many of the UDF galaxies have metallicity estimates from the deep MUSE UDF initiative. These measurements indicate that most of the galaxies under consideration are consistent with solar metallicities (Boogaard et al., 2019). Ultimately, the combined information can be used to derive molecular gas (H_2) mass functions for the different redshift bins covered by the observations. In an additional step, the total molecular gas mass can be summed in a specific redshift bin. As the cosmic volume is well defined for each redshift bin through the ASPECS setup, the cosmic density of the molecular gas can be derived by dividing the total H_2 mass by the volume, as discussed below.

Figure 8 shows the cosmic molecular gas density as a function of redshift. The key result here is that the H_2 gas density peaks at around $z = 2$ and then declines by almost an order of magnitude to the value measured in the local Universe. This behaviour was suggested in previous CO deep fields, including the ASPECS pilot programme, but the error bars now enable us to firmly conclude that there is an increase and then a decline in the gas density with cosmic time. The results are also consistent with gas masses derived from dust continuum measurements, including those using the ASPECS

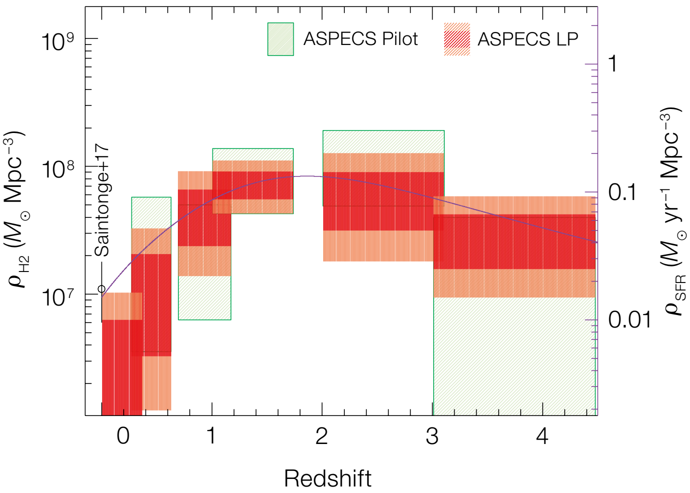

Figure 8. The cosmic evolution of the density of the molecular gas mass as a function of lookback time. The results derived from ASPECS are shown as red boxes (Decarli et al., in preparation). The measurements are anchored at $z = 0$ through the measurement by Saintonge et al. (2017). There is an unambiguous decline of the molecular gas density from redshifts $z \sim 2$ to today by about an order of magnitude. For comparison, we also show the evolution of the star formation rate density in purple (see units on the right y-axis, Madau & Dickinson [2014]) that shows a similar decline from the peak of the "epoch of galaxy assembly" at $z \sim 2$ to today.

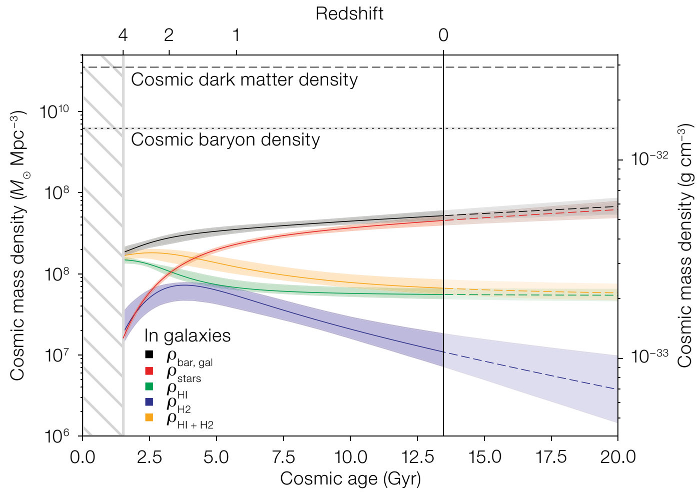

Figure 9. The ASPECS measurement of the evolution of the molecular gas content, ρ_{H2} (blue line) is shown together with other baryonic components that are associated with galaxies. These are: the stellar mass (shown in red), and the atomic gas phase (HI, shown in green). The sum of atomic gas and molecular gas is also plotted (yellow line). For completeness, the cosmic baryon density and cosmic dark matter density are also shown. The vertical line at redshift $z = 0$ (top x-axis) indicates the current age of the Universe. A simple extrapolation of the curves shows that as the molecular gas density drops further in the future, the additional growth in stellar mass in galaxies will be marginal.

continuum map (Scoville et al., 2017; Liu et al., 2019; Magnelli et al., 2020). This peak of H_2 density corresponds to the peak in the star formation history ("the epoch of galaxy assembly"). We next discuss the implications of the ASPECS results for galaxy formation.

The cosmic baryon cycle

The ASPECS survey allows the determination — from an unbiased selection — of the evolution of the cosmic molecular gas density from low redshift out to within 2 Gyr of the Big Bang. This behaviour can now be put in context with other key estimates of galaxy properties, in particular the evolution of the cosmic density of star formation rate and the build-up of stellar mass. In Figure 9 we compare our ASPECS results for molecular gas with other baryonic phases that are associated with galaxies, most notably the stellar mass and the atomic gas (HI). The stellar mass, which is characterised with multi-band optical/near-infrared imaging, constantly builds up over cosmic time, to first order following the time integral of the cosmic star formation rate density (Madau & Dickinson, 2014). The density of atomic hydrogen, on the other hand, shows little variation as a function of lookback time. The behaviour of the atomic gas is in stark contrast to the rise and fall of the molecular gas density, as derived by ASPECS. It should be noted that at a cosmic age of about 4 Gyr the H_2 density reached that of the HI, but stays below the HI at all other times. At around the same age of the Universe, the stellar mass density surpasses that of the total (cold) gas, as seen in HI + H_2.

The masses/densities of the molecular and atomic gas seen at high redshift imply that their masses are insufficient to account for the stellar mass budget seen in today's Universe. Together with other measurements, the ASPECS results constrain the accretion rates of gas from the circum- and inter-galactic medium — the accretion that is necessary to explain the stellar mass growth. As such, it provides constraints on a key component in the cosmic baryon cycle in galaxies (Walter et al., 2020).

The current age of the Universe is indicated by a vertical line at a cosmic age of 13.7 Gyr in Figure 9. Under the assumption of continuity we can use empirical fitting functions to forecast the evolution of the baryon content associated with galaxies over the next few Gyr. Assuming that our fits can indeed be extrapolated into the future, the molecular density will decrease by a factor of two over the next 5 Gyr, whereas the HI and stellar mass densities will remain approximately constant. The star formation rate density will follow the decrease of H_2. In this scenario, today's Universe has entered "Cosmic Twilight", during which the star formation activity in galaxies inexorably declines, as the gas inflow and accretion shut down.

Other topics addressed by ASPECS

For completeness, it should be mentioned that other investigations have been carried out using the ASPECS dataset. These studies include stacking experiments, both in the image plane and in redshift space (3D), capitalising on the rich spectroscopy from deep MUSE initiatives in the field (Bacon et al., 2017; Inami et al., 2017). These studies showed that most of the emission (both in the dust continuum and CO) in the field is accounted for by the detection of individual galaxies (Inami et al., in preparation). CO intensity mapping of the field also concluded that the majority of the CO emission in the field is detected by the current observations (Uzgil et al., 2019). We also compare results from ASPECS to predictions from two cosmological galaxy formation models, the IllustrisTNG hydrodynamical simulations and the Santa Cruz semi-analytic model (Popping et al., 2019).

Next (observational) steps

The ASPECS observations were designed to maximise the sensitivity to molecular gas, which in turn did not result in spatially resolved observations. Now that ALMA has pinpointed which galaxies in the UDF are rich in dust and gas emission, the next step will be to spatially resolve the distribution of molecular gas and dust in individual galaxies with dedicated high-resolution ALMA observations. A particularly interesting goal is to determine the dynamics of the gas, including rotation, turbulence, infall, or outflow. Another goal is to obtain ALMA multi-band observations of these galaxies in order to further quantify the state of the molecular gas (for example, density, temperature). The galaxies in the UDF will also be the target of major observing campaigns with the upcoming James Webb Space Telescope (JWST). In this context ALMA will continue to play a key role in constraining the physical properties of galaxies near the peak of cosmic star formation ($z \sim 2$), and beyond.

Acknowledgements

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Notes

[a] The ASPECS collaboration is led by PIs Manuel Aravena [UDP, Chile], Chris Carilli [NRAO, USA], Roberto Decarli [INAF, Italy] and Fabian Walter [MPIA, Germany], and consists of 40 scientists from 35 institutions in 9 countries, including: Roberto Assef (UDP, Chile), Roland Bacon (Univ. Lyon, France), Franz Bauer (PUC, Chile), Frank Bertoldi (AIfA, Germany), Leindert Boogaard (Leiden Obs., Netherlands), Rychard Bouwens (Leiden Obs., Netherlands), Thierry Contini (LATT, France), Paulo C. Cortes (JAO, Chile), Pierre Cox (IAP, France), Elisabete da Cunha (UWA, Australia), Emanuele Daddi (CEA Saclay, France), Tanio Diaz-Santos (UDP, Chile), David Elbaz (CEA Saclay, France), Jorge Gonzalez-Lopez (UDP, Chile), Jacqueline Hodge (Leiden Obs., Netherlands), Hanae Inami (Univ. Hiroshima, Japan), Rob Ivison (ESO), Melanie Kaasinen (MPIA, Germany), Olivier Le Fevre (LAM, France), Benjamin Magnelli (AIfA, Germany), Marcel Neeleman (MPIA, Germany), Mladen Novak (MPIA, Germany), Pascal Oesch (Geneva, Switzerland), Gergo Popping (ESO), Dominik Riechers (Cornell Univ., USA), Hans-Walter Rix (MPIA, Germany), Mark Sargent (Sussex Univ., UK), Ian Smail (Durham Univ., UK), Rachel Somerville (Flatiron Institute, USA), Mark Swinbank (Durham Univ., UK), Bade Uzgil (NRAO, USA), Paul van der Werf (Leiden Obs., Netherlands), Jeff Wagg (SKA, UK), Axel Weiss (MPIfR, Germany), Lutz Wisotzky (AIP, Germany).

Sangku Kim/ESO

ALMA, located in the Chilean Atacama desert, is the most powerful telescope for observing the cool Universe — molecular gas and dust.

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The Araucaria Project Establishes the Most Precise Benchmark for Cosmic Distances

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In the last 20 years, over the course of the Araucaria project, we have studied 20 very special eclipsing binary systems in the Large Magellanic Cloud (LMC). Based on these systems and our newly calibrated surface brightness–colour relation we have measured a distance to the LMC that is accurate to 1%. This is currently the best benchmark for cosmic distances and it will therefore impact several fields of astrophysics. In particular, it has allowed a determination of the Hubble constant with a precision of 1.9%.

Figure 1. The Large and Small Magellanic Clouds in the southern sky.

Introduction

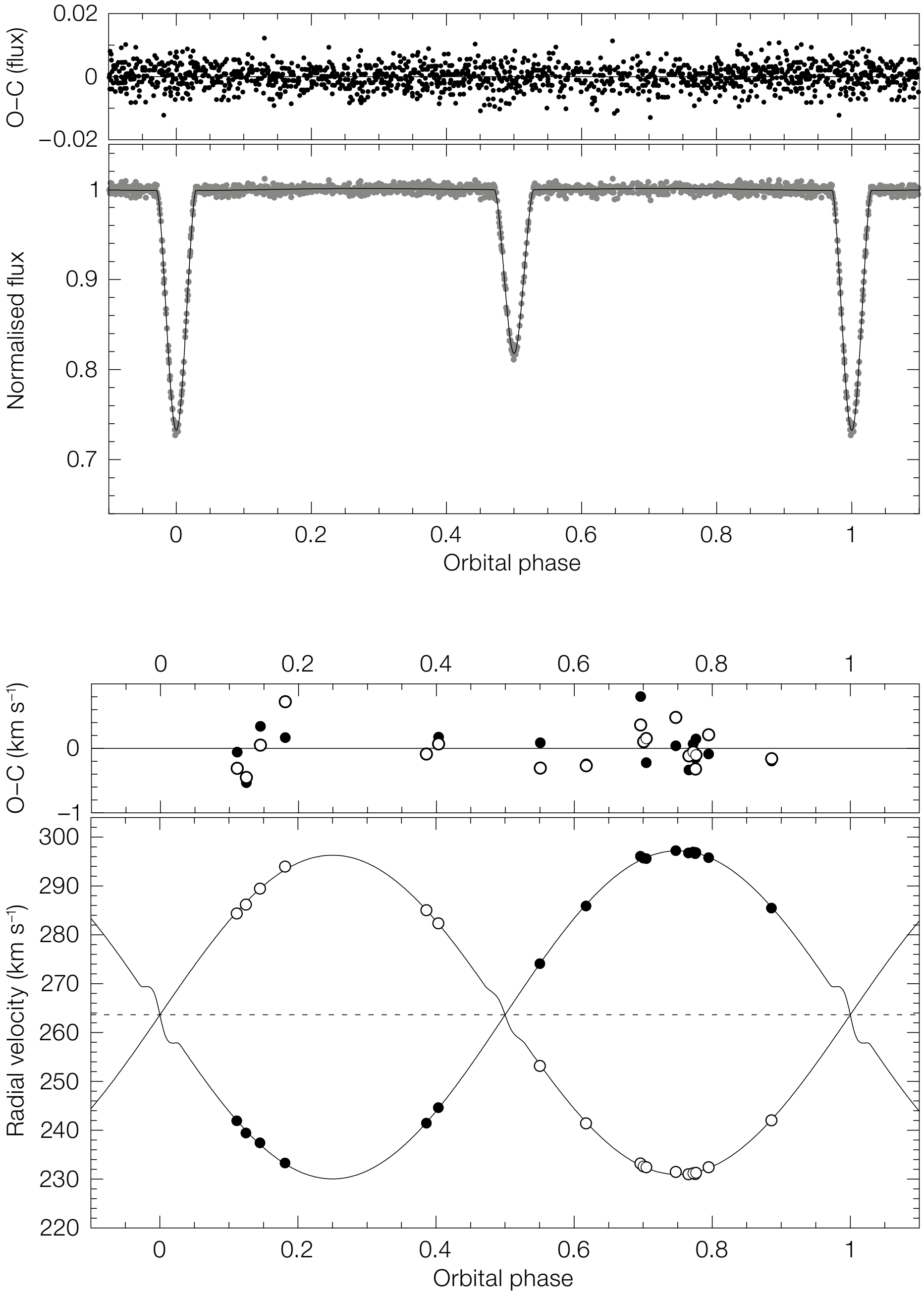
Since the earliest observations in ancient times to present-day astrophysics, the determination of distances to astrophysical objects has been one of the most important, fascinating and challenging goals in astronomy. Knowing distances is about much more than just knowing the scale; it also means knowing the physical nature of the objects in the Universe, and each significant improvement in the accuracy of the distance scale has traditionally opened up new fields of astrophysical research.

Distance determinations to galaxies led to the discovery of the expansion of the Universe, one the most important breakthroughs in astrophysics. Since then the precise and accurate measurement of distances to galaxies provides the basis for determining the famous "Hubble constant" (H_0) which describes the expansion rate of the Universe and has become a central problem in astrophysics.

After the detection of the accelerated expansion of the Universe and the introduction of an enigmatic dark energy component to the matter-energy content of the Universe, the physical explanation of the nature of dark energy has become a major challenge for astronomers and physicists. Recent empirical determinations of H_0 have further complicated our understanding of the Universe. The most precise empirical determination of H_0 to date is 74.03 ± 1.42 km s^{-1} Mpc^{-1} and is based on Cepheids and Type Ia supernovae (Riess et al., 2019). The value obtained differs by about 4σ from the value predicted by the Planck Collaboration et al. (2016), which is based on a ΛCDM model and the Planck CMB data (66.93 ± 0.62 km s^{-1} Mpc^{-1}). This discrepancy between the two values of H_0 is sometimes called a crisis, and may indicate the need for new physics beyond the standard cosmological model. A significant improvement in the accuracy of the measurement of H_0 by the Cepheid-supernova Ia method is therefore of paramount importance for deciding if the current discrepancy between it and the Planck H_0 value does indeed exist. This is critical for cosmology in general, and necessary to drive truly significant progress towards the understanding of the dark energy phenomenon.

After about 100 years of intensive work on the empirical determination of the Hubble constant, it is evident that any significant reduction in its uncertainty can now only be achieved by improving the accuracy of the absolute calibration of the Cepheid method, which constitutes the largest contribution to the total error budget of the H_0 determination (see, for example, Riess et al., 2018).

Figure 2. The light curve and radial velocity curve and corresponding residuals obtained for one of our target eclipsing binaries in the LMC, demonstrating the high quality of the data. Based on observations such as these we obtained stellar physical parameters with a very good precision of 1–2%.



The Large Magellanic Cloud as a perfect astrophysical laboratory

The Large Magellanic Cloud (LMC), which can be seen with the naked eye in the southern sky (Figure 1) is our closest neighbour galaxy and provides the road to calibrating Cepheids and other distance indicators. Indeed, it possesses a large population of Cepheids (Soszynski et al., 2017), has a relatively simple geometry (see, for example, van der Marel et al., 2002), and relatively small extinction (Gorski et al., 2020). Exquisite period–luminosity relations have already been obtained based on the LMC Cepheids in both optical and near-infrared bands (Soszynski et al., 2017; Persson et al., 2004).

The LMC is also the perfect laboratory with which to study many different processes and objects. Therefore, a precise geometrical distance to this galaxy is extremely important, not only for cosmology, but also for many different fields of modern astrophysics. For this reason, more than 600 distance determinations to the LMC can be found in the literature (with the NED database, Mazzarella & the NED team, 2007). However, their relatively low precision and lack of control of systematic errors prevent the use of the LMC distance to significantly improve the determination of H_0.

Eclipsing binaries as precise and accurate distance indicators

Detached eclipsing double-lined spectroscopic binaries offer a unique opportunity to measure directly, and very accurately, stellar parameters like mass, luminosity, and radius, and consequently the distance (Graczyk et al., 2014; see also Kruszewski and Semeniuk, 1999 for a very detailed historical review).

With current observational facilities, and the application of an appropriate surface brightness-colour relation, eclipsing binaries have the potential to yield the most direct (one-step), and the most accurate (~ 1%) distance to the LMC. Indeed, the distances to individual systems can be obtained from the simple equation:

$$d(pc) = 9.2984 \times \frac{R(R_\odot)}{\varphi(mas)}$$

The linear radii of the components of the binary systems R are determined from the standard, well known modelling of radial velocities and photometric light curves, while angular diameters are derived from the surface brightness-colour relation. The surface brightness is defined as $S_V = V_0 + 5\log(\varphi)$, where V_0 is the V-band magnitude corrected for the reddening and φ is the stellar angular

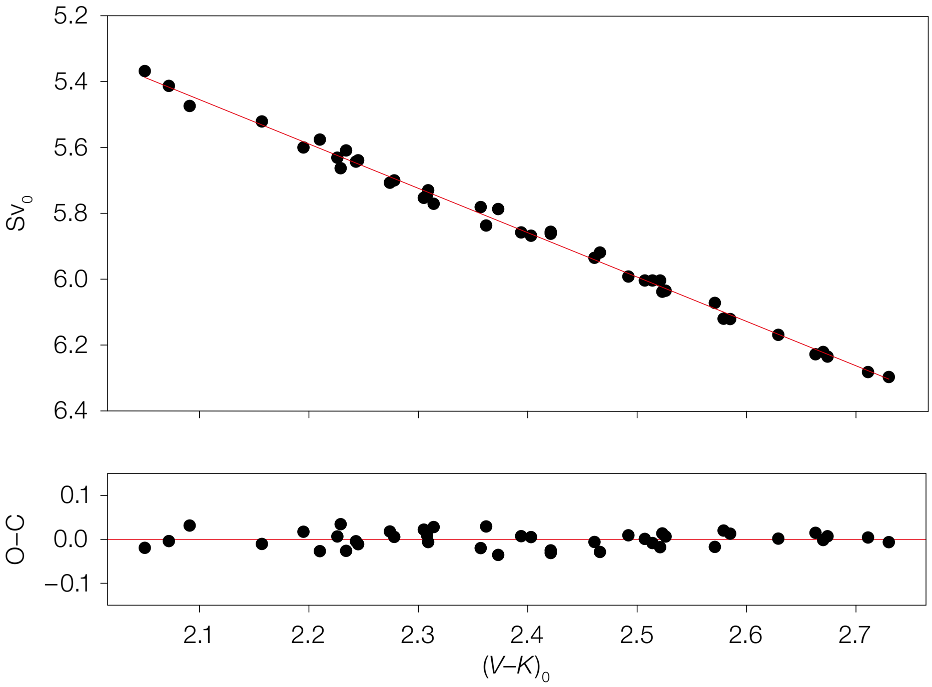


Figure 3. The new surface brightness–colour relationship obtained over the course of the Araucaria project based on interferometric observations with the VLTI and PIONIER and photometric data from the literature. The rms scatter on this relation is 0.018 magnitudes, which corresponds to 0.8% precision in stellar angular diameters.

diameter. An empirical surface brightness-colour relation is very well established for stars with spectral types later than A5, coming from accurate determinations of stellar angular diameters using interferometry (Di Benedetto, 2005; Kervella et al., 2004; Pietrzyński et al., 2019).

The only concern in using this approach was that late-type main sequence binaries located in the LMC are too faint to secure accurate high-resolution spectra even with the biggest telescopes. For a long time, it had not been possible to use the full potential of eclipsing binaries to determine the distance to the LMC because of the lack of suitable systems. This situation changed when microlensing teams, in particular the Optical Gravitational Lensing Experiment (OGLE), provided an enormous amount of precise photometric data for about 35 million stars in the LMC obtained over around 20 years. Based on these data a few dozen extremely rare binaries composed of helium-burning giants were detected (Graczyk et al., 2011). The orbital periods of such systems are very long, typically several hundred days, and the eclipses are very narrow, which explains why they are extremely difficult to discover.

The Araucaria project delivers a 1% geometrical distance to the LMC

About 20 years ago we began a long-term study called the Araucaria project with the aim of improving the calibration of major stellar distance indicators, and, as a result, the determination of the Hubble constant (Gieren et al., 2005; Pietrzyński et al., 2019). The eclipsing binaries were a very important part of this from the very beginning. In particular, we selected a sample of binaries composed of helium-burning giants in the LMC and we have collected high-quality spectroscopic data with the MIKE, HARPS and UVES high-resolution spectrographs, and near-infrared photometry with the SOFI camera at ESO's La Silla Observatory (see Figure 2). We then used these data together with OGLE photometry to determine very precise astrophysical parameters for the systems (1–3% masses, radii, temperatures, etc.).

In 2013, based on our analysis of eight eclipsing binaries and applying the surface brightness-colour relation of Di Benedetto (2005) we managed to measure a 2% distance to the LMC (Pietrzyński et al., 2013). We demonstrated that our result was only weakly affected by a number of factors, including reddening, metallicity, gravity, limb darkening and blending. Indeed, the method is very simple and powerful and provides a unique opportunity to precisely quantify all possible error contributions (Pietrzyński et al., 2013; Graczyk et al., 2014). The total error budget of this measurement is completely dominated by the error in the surface brightness-colour relation of Di Benedetto (2005). The root-mean-square (rms) scatter on this relationship is 0.03 magnitudes, which translates to 2% precision in the determination of the angular diameter. The observed scatter is mainly caused by observational errors on the *K*-band magnitudes. Another very important issue while striving for 1% accuracy of the surface brightness-colour relation calibration is to ensure that the angular diameters are measured uniformly and that all stars are at comparable evolutionary phases as the components of the LMC eclipsing binaries.

In order to provide a significantly improved calibration of the surface brightness-colour relation, we carefully selected a sample of 41 nearby red clump giants, which are in the core helium burning phase of stellar evolution. We made sure that our sample does not contain variable stars or binaries. For our sample stars we collected precise near-infrared photometry at the South African Astronomical Observatory (Laney, Joner & Pietrzyński, 2012), and angular diameters to a precision of 1% using the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER) instrument on ESO's Very Large Telescope Interferometer (VLTI) (see Gallenne et al., 2018). These data are complemented with high-quality homogenous *V*-band photometry (Mermilliod, Mermilliod & Hauk, 1997). Based on these exquisite data, the following surface brightness-colour relation was obtained:

$$S_V = 1.330(\pm\ 0.017) \times [(V–K)_0 - 2.405] + 5.869(\pm\ 0.003) \text{ magnitudes},$$

with a rms scatter of 0.018 magnitudes. The relation is presented in Figure 3. It

Figure 4. Location of our 20 eclipsing binaries in the LMC. As can be seen here, all of them are located close to the centre of the LMC and to its line of nodes. The final LMC distance derived is only very weakly dependent on the geometry of this galaxy.

allows the measurement of angular diameters with a precision of 0.8%, and therefore distances to eclipsing binaries with a precision close to 1%.

We then applied our new surface brightness-colour relation to measuring distances to 20 eclipsing binaries located in the LMC. The location of the binaries is shown in Figure 4. The individual distances are precise to 1.5–2%. Combining them, the following distance measurement to the centre of the LMC was obtained: 18.477 ± 0.004 (statistical) ± 0.026 (systematic) magnitudes. With 20 precise individual distances we constrained the geometry of the central parts of the LMC and convincingly demonstrated that the geometrical extent of the galaxy has no influence on the distance measurement within the quoted errors.

To demonstrate that the method delivers, not only precise but also accurate distances, one has to compare results from independent methods. Pietrzyński et al. (2019) measured the distance to the nearby eclipsing binary TZ For at 185.1 ± 2.0 (stat) ± 1.9 (sys) pc using exactly the same approach as for the LMC systems. A very precise distance to TZ For of 186.1 ± 1.0 (stat+syst) pc was also obtained based on spectroscopic and astrometric orbits (Gallenne, 2016). These two independent geometrical distance determinations are in an excellent agreement.

With the final Gaia parallaxes expected a few years from now, a comparison between Gaia distances and distances determined for binaries with our surface brightness-colour relation will be performed for many eclipsing binaries at the 1% level. This work will allow us to definitively mutually test and verify the accuracy of our method against Gaia.

A new benchmark for cosmic distances

As can be appreciated from Figure 5, eclipsing binaries offer us an opportunity to determine stellar distances at a similar level of precision to that of Gaia at 1 kpc from the Sun, and to retain that precision out to the outskirts of the Local Group of galaxies. With the advent of the new extremely large telescopes in the near future, this will be extended even to galaxies far beyond the Local Group.

The precise and accurate distances from this one-step geometrical method will continue to be very important for several reasons. They provide the unique possibility of measuring geometrical distances to nearby galaxies, which is very important for a wide variety of studies. As we already mentioned, independent distances to nearby eclipsing binaries will allow a cross-check with Gaia parallaxes at the level of 1%, which is extremely important for evaluating the accuracy of both techniques. Finally, the method provides an independent precise zero point for the extragalactic distance scale and the calibration of the Cepheid period-luminosity relation in different environments, paving the way for a precise determination of the Hubble constant from the combined Cepheid period-luminosity relation — supernova Ia method.

Indeed our 1% LMC distance has already allowed a precise calibration of the LMC Cepheids and, as a result, a determination of H_0 to a precision of 1.9% (Riess et al., 2019). Moreover, it has allowed a precise calibration of another interesting distance indicator, the tip of the red giant branch (Gorski et al., 2018; Freedman et al., 2020). This method was then used to obtain H_0 in an independent way (Freedman et al., 2020).

Summary and future work

Eclipsing binaries composed of late-type stars have become a unique tool for the precise measurement of distances within a volume of about 1 Mpc. We would like to highlight the role of interferometric measurements of stellar diameters in calibrating the surface brightness-colour

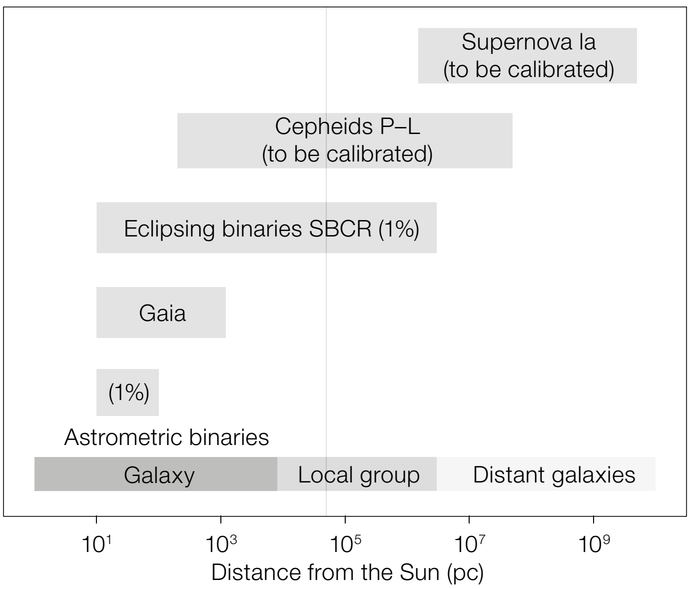


Figure 5. The methods that can be used to calibrate the Cepheid period-luminosity relation and, as a result, the brightness of Type Ia supernovae. Eclipsing binaries, together with our new relation, offer us the opportunity to determine distances competitive in precision to those with Gaia at about 1 kpc from the Sun. Contrary to Gaia parallaxes, however, they retain their high precision for distances up to 1 Mpc.

Figure 6. One of the auxiliary telescopes forming the VLTI; these telescopes were crucial in our project. Photograph taken by Grzegorz Pietrzyński during one of the team's frequent observations of the LMC eclipsing binaries at ESO's Paranal observatory.

relation, which is at the heart of this method. Thanks to this, our method is completely independent and does not require any calibrations or assumptions. It has opened up the opportunity to measure geometric distances to nearby galaxies with an accuracy of about 1%, which is very important for many fields of modern astrophysics. In particular it allows the precise calibration of secondary distance indicators like Cepheids and the tip of the red giant branch and, as a result, to significantly improve the determination of the Hubble constant.

Despite this significant progress in using eclipsing binaries as a precise and accurate distance indicator, a lot of work is still required before we can realise the full potential of eclipsing binaries and apply them to measuring cosmic distances on a larger scale. Our team has been working intensively on improvements to the surface brightness-colour relation. We are working on precision calibration of the surface brightness-colour relation for early-type stars (Taormina et al., 2019, 2020). Eclipsing binary systems composed of such stars are much easier to discover in nearby galaxies than systems composed of the late-type giants that we have studied in the LMC.

We have also been working on a very extensive verification of our method. We have already obtained astrometric orbits with the VLTI and PIONIER for more nearby eclipsing binaries (Gallenne et al., 2019). Moreover we have prepared an extended list of eclipsing binaries which can be analysed with even greater precision, and for which we expect very precise Gaia parallaxes (see, for example, Graczyk et al., 2019). These data will allow us to compare very precise (better than 1%) distances from three independent methods and verify their accuracy.

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Photographs taken at the Paranal Observatory (above) and in Garching (below) in February 2019 to celebrate the International Day of Women and Girls in Science.

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ESO's Peer Review Panel Achieves Gender Balance

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Gender equality, diversity and inclusion are very high on ESO's agenda, and the organisation has undertaken a number of initiatives in these areas over the past decade (Primas, 2019). The reasons behind these actions are not limited to addressing the issue internally; ESO also aims to raise awareness, with the aim of setting high standards that will motivate members of the scientific community, and hopefully beyond. A diverse and inclusive environment constitutes the most favourable terrain for the growth of ideas, creativity, and the development of original projects — key drivers of success.

Although gender balance is not the only ingredient for ensuring diversity, it is certainly an area which can be closely monitored, and relatively simple corrective actions taken. Several large astronomical facilities, including the Hubble Space Telescope (HST), ESO and the Atacama Large Millimeter/submillimeter Array, have closely scrutinised the processes used by the peer review committees that allocate time. While investigating possible biases (Reid, 2014; Patat, 2016; Carpenter, 2020), these studies have consistently revealed the presence of systematics — at face value female scientists are less successful at getting telescope time. Although the problem is complicated by a number of factors, for instance, the difference between the average scientific seniority profiles in female (F) and male (M) samples, it is clear that the matter cannot be dismissed.

One of the issues resides right at the source, in the lack of gender balance present in the scientific communities that these organisations serve. In the case of ESO users, the overall female:male ratio is about 30:70 (Patat, 2016). One consequence is that, for instance, the gender composition of committees taking decisions on scientific matters is itself unbalanced.

The challenges associated with achieving gender balance intensify when one looks at the more senior levels. The fact that there are fewer scientists at more advanced career levels (see, for instance, Primas, 2019) can generate a negative feedback loop; senior female researchers experience more pressure to serve on committees, and at some point have to start limiting the numbers of requests they are able to accept, thus inadvertently and for purely structural reasons this increases the imbalance.

At ESO it is possible to see the impact of this during the recruitment of the referees serving on the Observing Programmes Committee (OPC), which is composed of 78 panelists. On average, every semester ESO needs to replace 32 members (~ 40%), selecting from the nominations provided by the Users Committee and taking into account a number of constraints. Ensuring good gender balance in the OPC has always been difficult, both because of the imbalance in the community and because of the higher rejection rate from female candidates.

This notwithstanding, the Observing Programmes Office (OPO) proactively addresses this issue during the recruitment of referees for peer review, aiming to increase diversity and representation on the panels. The result of this continuing effort is presented in Figure 1, which shows the fraction of female referees over the last eight years, during which 553 referees from 30 different countries reviewed about 14 000 proposals. As of Period 99, the overall female fraction has been consistently larger than the 30% value which is representative of ESO's community. That fraction has continued to grow, and the 50% level was reached in Period 105. To the best of our knowledge, this is the first time this has happened in ESO's history. Lower values are attained in the composition of the OPC-proper (orange line in Figure 1), which includes only the panel chairs. This reflects the difficulty one faces in recruiting female scientists at the more senior levels and for smaller committees, where one or two rejections during recruitment can have a disproportionately large impact.

The systematic trend seen in Figure 1 is reassuring but it is certainly not sufficient to guarantee equality and inclusion over the long term. Other measures under consideration or being actively deployed include raising awareness about unconscious bias in peer review panels, obfuscating information on proposing teams and introducing a dual-anonymous peer review. The recent change requiring the user community to add gender information to User Portal profiles[1] will help ESO to closely monitor the effectiveness of these and other measures.

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Links

[1] Announcement requesting users to provide additional information in their ESO User Portal profiles: https://eso.org/sci/publications/announcements/sciann17266.html

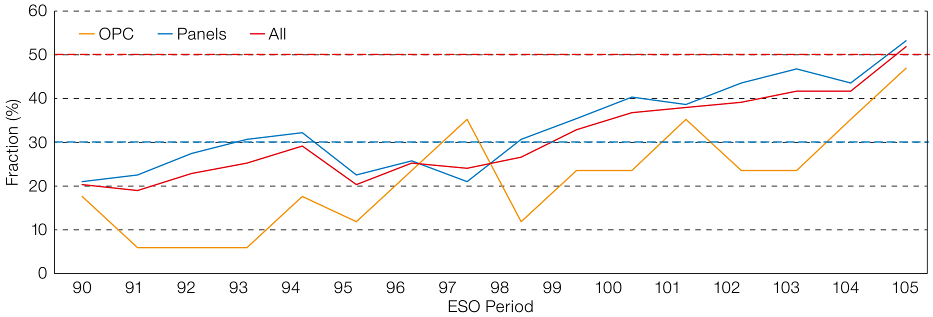

Figure 1. The change in the gender balance on the Observing Programmes Committee and panels over Periods 90–105 (2012–2019).

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Report on the ESO Workshop

The Galactic Bulge at the Crossroads

held at Gran Hotel, Pucón, Chile, 14–19 December 2018

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Manuela Zoccali[2, 3]
Dante Minniti[3, 4, 5]
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[6] Universidad de Concepción, Chile
[7] Universidad de La Serena, Chile

The Galactic bulge is of great interest to researchers working in several different areas and it has seen a surge of interest in recent years; indeed, half of the papers discussed at the meeting were published after 2014. This interest is motivated for several reasons: it is a primary component of the Milky Way, comprising ~ 25% of its stellar mass; and all major stellar populations intersect there, reaching their highest densities, thus making it truly a crossroads. Its formation is intimately related to that of the Milky Way, therefore it offers clues to understanding the structure, formation, and evolution of the Galaxy. A variety of bulge morphologies are seen in the local Universe, so a comparative study of the properties of the Galactic bulge helps with understanding bulge formation in general. Finally, ever more detailed studies of galaxies at high redshift promise to catch Milky Way proxies in their infancy, thus revealing the initial conditions of bulge formation. All of these aspects were reviewed by invited and contributed talks, and in poster sessions.

Motivations

In March 2017, some of the participants at the conference "On the Origin (and Evolution) of Baryonic Galaxy Halos" met over dinner at Puerto Ayora to consider the organisation of a conference in Chile to discuss recent progress on the Galactic bulge. A workshop proposal was then submitted to ESO, which was successful. Following intense preparatory work, coupled with additional fund raising, the meeting started on the afternoon of Sunday 9 December 2018, with a welcome cocktail on the terrace of the Gran Hotel Pucón. The hotel offers stunning views of the Villarrica lake. Later in the week, the weather was mostly cloudy, but interestingly, on Wednesday the sky cleared just in time to let us enjoy the free afternoon — set apart in the programme — and the impressive view of the Villarrica volcano was finally revealed! The day after, the weather was cloudy again, but in the evening the hotel terrace was illuminated by the folklore group *MasDanza*, who provided participants with a fascinating show of Easter Island dances, ahead of dinner at the hotel restaurant. The venue hosted five days of excellent presentations and lively discussions, which started on Monday morning with a welcome address by the deputy mayor of the city of Pucón. The healthy diversity of the participants is also worth stressing, with significant representation from the Chilean astronomical community, demonstrating its impressive growth in the last few years.

This article presents just a short summary of the main results that emerged during the conference, and their possible interpretation. This is followed by a discussion of open questions and the scope for future research.

The basic facts

An impressive array of new observations was presented at the conference, so we attempt here to give the current overall picture of the Galactic bulge. This overview is of course biased, both because only a fraction of the literature was presented, and because it is based on our own interpretation of what was discussed. For a more comprehensive view, we refer readers to the Zenodo link to the presentations[1], and to the reviews listed in Table 1.

Authors	Title
Kormendy & Kennicutt (2004)	Secular evolution and the formation of pseudobulges in disc galaxies
Somerville & Davé (2015)	Physical models of galaxy formation in a cosmological framework
Bournaud (2016)	Bulge growth through disc instabilities in high-redshift galaxies
Brooks & Christensen (2016)	Bulge formation via mergers in cosmological simulations
Fisher & Drory (2016)	An observational guide to identifying pseudobulges and classical bulges in disc galaxies
Shen & Li (2016)	Theoretical models of the Galactic bulge
Naab & Ostriker (2017)	Theoretical challenges in galaxy formation
Barbuy, Chiappini & Gerhard (2018)	Chemodynamical history of the Galactic bulge

Table 1. A list of recent reviews related to the formation of galactic bulges[a].

Like the Milky Way, most spiral galaxies populating the local Universe are barred (~ 60%); and if their mass is similar to that of the Milky Way, they have an 80% chance of having boxy or peanut-shaped bulges with high levels of cylindrical rotation. Velocities in the strongest barred galaxies are like those in the Milky Way. In addition, recent integral-field unit observations of barred discs show kinematics that are consistent with the Galactic bulge. Cosmological simulations are consistent with this picture; their end products are mostly pseudo-bulges formed *in situ*, with a fraction of them containing a classical component.

The emerging picture of the Galactic bulge is that of three components with different metallicities and different cylindrical rotation speeds, which first appear as a bimodal metallicity distribution function (MDF) with a metal-poor tail, and because the relative fraction of metal-rich to metal-poor stars decreases far from the Galactic plane, a vertical metallicity gradient is observed. The two main structures are a spheroidal bar with [Fe/H] ~ −0.5 and alpha-enhanced stars, with relatively slow rotation; and a boxy bar at [Fe/H] ~ +0.3 which can be further split into a slower, more metal-poor component ([Fe/H] ~ –0.24) and a faster, more metal-rich component ([Fe/H] ~ +0.18). The boxy bar hosts stars with solar to below-solar alpha-enhancement abundances. Furthermore, an X-shaped component (a manifestation of a boxy/peanut structure) becomes more and more evident as metallicity increases. B/P components are thought to be the inner 3D parts of a longer, flatter bar such as seen in NGC 4314, which has been detected by Wegg, Gerhard & Portail (2015).

The run of alpha elements vs. iron indicates that stars in the boxy component were formed later, and at a lower rate compared to the spheroidal component. However, while star formation certainly started more than 10 Gyr ago, as signaled by blue horizontal branch stars, the subsequent star formation history is still a matter of debate, with some studies finding an age-metallicity relationship extending to 3 Gyr ago. Indeed, cosmological simulations that can resolve bulges predict complex star formation histories, so reaching a consensus on the age distribution of Millky Way bulge stars will be essential to validate them and the evolutionary timeline pictured below.

The presence of a pressure-supported, classical bulge is still debated, but a non-rotating system of 43 confirmed globular clusters indicates that a relic of such a component should be present, even if significantly less massive than the others described above.

A small population of metal-poor ([Fe/H] < –1) stars not belonging to any of the above components is also detected, which could either be another signature of a minor classical bulge, or the inner extension of the Galactic halo. RR Lyrae stars have metallicities comparable to those of these stars, but it is unclear whether both belong to the same population; they are not rotating and might be a relic of an accreted system.

Finally, there exists a nuclear bulge of $1.4 \times 10^9 M_\odot$, which consists of an r^{-2} nuclear stellar cluster at the centre, a large nuclear stellar disc with radius 230 pc and scale height 45 pc, and the nuclear molecular disc of same size. And of course, at the very centre sits the supermassive black hole, which constitutes about 15% of the bulge mass.

Figure 1. Conference photo.

Open questions

While there appears to be broad consensus on the main characteristics of the Galactic bulge, it appeared at the conference that many fundamental questions still remain to be answered. We try to capture some of the main ones in the following paragraphs.

Age of bulge stars

For several decades the consensus has been that bulge stars are as old as those of Galactic globular clusters. However, some recent studies, (such as those of one of the speakers, Thomas Bensby), have suggested that younger stars could also be present in those regions. Using helium-enhanced isochrones might reduce Thomas's ages somewhat (Nataf & Gould, 2012; Nataf, 2017), but the conundrum is not completely solved. Elena Valenti and Cristina Chiappini suggested that this controversy might be solved by asteroseismology, which could yield ages with 20% uncertainties.

To stress the difficulty of obtaining ages, Elena Valenti pointed out that, even starting from the same set of Hubble Space Telescope (HST) photometric data, Renzini et al. (2018) and Bernard et al. (2018) come to different results. The latter find that most stars were formed earlier than 8 Gyr ago, while the former find that no more than ~ 3% of the metal-rich component can be ~ 5 Gyr old.

More support for old ages came from Francisco Nogueras Lara and his survey called GALACTICNUCLEUS (Nogueras-Lara et al., 2018), which uses the High Acuity Wide field *K*-band Imager (HAWK-I) at the VLT in combination with speckle holography (Schödel et al., 2013). On the other hand Francesca Matteucci predicts a non-negligible fraction of young stars, by modelling magnesium abundances vs. iron from Rojas-Arriagada et al. (2017).

How many MDF peaks?

The metallicity distribution function (MDF) was extensively discussed by Alvio Renzini, Christina Chiappini, Manuela Zoccali, and Thomas Bensby. While all authors agree on a broad metallicity range of –1.5 < [Fe/H] < +0.5, the details of the MDF differ, in particular the number of peaks and their position, with the added complexity that the MDF depends on the projected spatial position. The greatest variety is seen in the more central regions, where either two (GIRAFFE Inner Bulge Survey, GIBS) or three (ARGOS survey) peaks are detected. Away from the centre the Bulge RAdial Velocity Assay (BRAVA) found only one peak corresponding to the metal-rich population, because the metal-poor one is more centrally concentrated. To solve this conundrum, sharing data among different groups was suggested, in order to understand the origin of discrepancies and reach a consensus on the MDF vs. location.

Figure 2. The local organising committee members at the kickoff meeting on 16 October 2017.

No X-shaped component?

The presence of the X-shaped component rests on the assumption that the two clumps seen near the red giant branch in colour-magnitude diagrams represent helium-burning stars at different distances. This assumption was challenged by Martín López-Corredoira and Young-Wook Lee. The latter recalled that most globular clusters host multiple stellar populations, with a fraction of their stars having enhanced helium abundances. Stars with higher helium abundance end up on a brighter red clump compared to those with normal helium abundance; thus if the two red clumps were due to different abundances, and not to different distances, then stars in the two red clumps could have come from disrupted globular clusters, and the 3D structure of the bulge would be a bar embedded in a bulge with a more classical origin that would have formed at high redshift.

Martín López-Corredoira supported the idea of the absence of an X-shape by showing that only old and metal-rich red clump stars have an X-shaped distribution, while other distance indicators do not recover it.

Abundances of bulge vs. thin and thick discs

Bulge formation scenarios could be constrained by checking whether the bulge stars could have come from the thin or the thick disc. One way to do this is by using abundance signatures, which were discussed by several speakers. The consensus was that the three populations do differ in the run of abundances vs. iron, but larger stellar samples would help to settle this topic (see, for example, talks by Bensby, Rojas-Arriagada, Barbuy, Zasowski).

Which bulge structures are defined by RR Lyrae stars?

As noted above, MDFs show a tail of stars that are metal-poor, at [Fe/H] < –1, but their numbers are too small to allow them to be reliably associated with one of the known components. Thus, whether RR Lyrae stars and the metal-poor tail of red clump stars belong to the same population, is still an open question.

Another puzzle is the discrepancy between the results of the VVV and OGLE surveys, as shown by Manuela Zoccali and Igor Soszynski. While the Optical Gravitational Lensing Experiment (OGLE) finds a barred spatial distribution (Pietrukowicz et al., 2015), the VISTA Variables in the Via Lactea survey (VVV) finds a spheroidal one (Dékány et al., 2013; Gran et al., 2015).

Outlook

In the course of their presentations, many speakers listed potential valuable additions that would be necessary to improve on our current knowledge about the bulge. Some of their main ideas are listed here.

Abundances:
- Measure abundances (alpha elements in particular) of RR Lyrae stars, to understand to which population they belong.
- Check the extent of the multiple-populations phenomenon in the bulge, by measuring sodium abundances from high-resolution spectroscopy.
- Confirm the relative fractions of stars in different metallicity intervals by collecting data for stars closer to the Galactic plane, where current surveys have a gap.
- Agree on a common abundance scale, perhaps by giving the same data to different groups and exploring ways to make them converge.
- Measure [Fe/H] of dwarfs (not microlensed ones) with future large-aperture telescopes.
- Follow up Gaia stars with the 4-metre Multi-Object Spectroscopic Telescope (4MOST).
- Measure helium abundances, for example by resuming the R-method, using detached red giant branch eclipsing binary twins, or with Wide Field Infrared Survey Telescope (WFIRST) asteroseismology.

Extinction:
- Get 3D extinction maps, using diffuse interstellar bands (DIBs) and proper motions from WFIRST, the Multi-Adaptive Optics Imaging CamerA for Deep Observations (MICADO), and the Japan Astrometry Satellite Mission for INfrared Exploration (JASMINE); also, higher-resolution maps of the variations of the extinction law across the bulge area.
- As shown by Kathy Vivas and Abhijit Saha, use RR Lyrae stars to obtain a reddening map at ~ 0.30 arcsecond resolution and use it to recover intrinsic colours of all stars in a region of the sky.

High-redshift observations:
- Find the time/redshift when the first bars can be seen.
- As suggested by Natascha Förster-Schreiber, exploit the improved spatial resolution of future instruments to increase the chances of detecting bars (for example, MICADO on ESO's Extremely Large Telescope will allow a 100-pc resolution at $z = 2$).
- Observe globular cluster formation — as suggested by Renzini (2017) — to

have a direct view of the origin of one of the bulge components.

Morphology:
– Prove or reject the existence of the X-shaped component with Gaia trigonometric parallax distances.

Ages:
– Measure ages via asteroseismology, to solve the age discrepancy issue. In addition, it would be interesting to give Thomas Bensby's spectra to other teams and see whether they can reproduce his results.

Complete census of bulge stellar clusters:
– For a census of clusters gravitationally bound to the bulge, we need to get their 6D kinematics and reconstruct their orbits, as noted by Angeles Perez-Villegas.
– Felipe Gran's talk was along the same lines and showed the promise of Gaia proper motions (coupled to the VVV survey) to discover new bulge clusters (he has already found a new one).

A wish list:
– Dante Minniti provided his own list of desirable data additions, which include Gaia Data Release 3, Vera C. Rubin Observatory observations of the Galactic plane and bulge, JWST observations of bulge RR Lyrae stars, the Multi-object Optical and Near-infrared spectrograph (MOONS) instrument for the VLT, and a *K*-band filter for WFIRST. He would also like to determine the specific frequency of globular clusters in the Milky Way and compare it to other galaxies.

Exploit current and future high-resolution and/or panoramic imagers:
– Roger Cohen highlighted the complementary nature of ground and space observations. Ground-based facilities offer higher flexibility, allowing observations in many bandpasses which permit spectral energy distribution (SED) fitting and determination of reddening values, followed by multi-object spectroscopy to characterise large samples of stars. Space observatories offer greater stability in the point-spread-function (PSF) thus allowing precise astrometry. This is the promise of the James Webb Space Telescope (JWST) with the caveat that in the bulge stars will be saturated down to the red clump.
– Sara Saracino showed the potential of the Gemini Multi-Conjugate Adaptive Optics System to obtain high-resolution imaging in the infrared, which can be matched to HST images in the optical.

Current and future surveys

Livia Origlia presented her view of the future of surveys aimed at the bulge stellar populations. These will represent a large jump in the number of stars with measured proper motions (VVV, UKIDSS, JWST, LSST, WFIRST), ages via main sequence turn-off photometry (JWST, LSST, ELT+MCAO imaging), and turn-off spectroscopy (extensive micro-lensing surveys and follow-up high-resolution spectroscopy at 8–10-metre-class telescopes, and then high resolution spectroscopy of main sequence stars with the ELT (for example using HIRES). Abundance and kinematics data will be obtained at low latitudes with multi-object spectroscopy and wide fields: for example, MOONS and later the Maunakea Spectroscopic Explorer (MSE); and integral-field units in dense fields (for example, with MUSE and ERIS on the VLT, and then HARMONI on the ELT). She also noted that multiplexing spectrographs will help with chemical tagging of stars but will not be enough for detailed chemical studies. For these, ELTs will be needed, in order to collect significant samples in a short time, such as with ELT/HIRES, which she described in more detail.

Formation

With the caveat that many aspects of the Galactic bulge are still being investigated, and thus the scenario will likely change in the future, we propose here a possible timeline that could link the findings presented above. This overview is based on talks by Alvio Renzini, Beatriz Barbuy, Manuela Zoccali, Sandro Tacchella, Juntai Shen, Victor Debattista, Natascha Förster-Schreiber, and Ignacio Gargiulo, but any misunderstandings are entirely ours!

While galaxy candidates are detected up to $z = 10$, there are only enough of them below $z = 8$ (i.e., ~ 13 Gyr-old candidates) to infer the cosmic star formation rate (SFR), which is about 15 times lower than its peak at $z \sim 2$. At all epochs most star formation happens in galaxies located on a main sequence, where the SFR is proportional to the stellar mass, up to a maximum of $10^{11}\ M_\odot$.

Cosmological simulations show gas flowing to the centre of such a protogalaxy, triggering a starburst. Then, as more gas is accreted in the outskirts, a disc forms. While observations show clumpy protogalaxies, in some simulations those clumps can survive and reach the centre, whilst in others they disperse quickly, so their significance in terms of galaxy evolution is not clear.

At $z = 6$ we start acquiring data on black hole accretion rates, which afterwards closely follow the trend in the cosmic SFR. At $z = 3.5$ we have the first measurements of the molecular gas fraction in galaxies, which decreases until today, when 90% of its mass has been converted into stars.

The star formation history of the Milky Way can be reconstructed from $z = 3$ (11.5 Gyr), at which point its stellar mass was ~ $10^9\ M_\odot$, or 2% of the current value. Then at $z = 2.4$ (11 Gyr) the first measurements of (negative) radial metallicity gradients are obtained in the discs of (lensed) galaxies.

At $z = 2$ the mass of the Milky Way would have grown to ~ $6 \times 10^9\ M_\odot$ or 30% of the current bulge mass. Observations of galaxies of that mass show that they are clumpy rotating discs, with no bar detected (clumps are luminous but minor in mass). Also, they have high velocity dispersion and gas density ~ 150 times that of a present galaxy with the same mass. Larger galaxies show central density enhancements (bulges) growing in importance with mass, until $10^{11}\ M_\odot$, when they are about 60% of the total mass. Observations at $z = 2$ have a 1.5 kpc resolution (for example, with the Wide Field Camera 3 WFC3 on HST), therefore in a galaxy like the Milky Way a central primordial bulge might go undetected. Indeed, the presence of globular clusters confined in the centre of the Galaxy suggests that a classical bulge must have been created in its early stages.

After a few hundred Myr, at $z \sim 1.5$, the Milky Way progenitor would have reached the mass of today's bulge. Because most of its stars are older than 8 Gyr, if the bulge was formed out of that early disc star formation should have stopped soon after $z = 1.1$. Possibly star formation was not reactivated because equatorial accretion streams had too high angular momenta to feed the bulge, which effectively remained "starved"; feedback from active galactic nuclei (AGN) could also have a role. On the other hand, some studies find evidence for the continuation of star formation after that epoch, so this remains an open question.

To account for observed correlations between metallicity and kinematics, stars should form continuously in a kinematically cool gaseous disc and acquire large radial random motions with time. Therefore younger, kinematically cooler, and more metal-rich stars should have coexisted in the $z = 2$ disc with older, radially hotter, and more metal-poor stars. According to models, age differences of 1–2 Gyr are enough to produce large observable differences in the properties of different [Fe/H] populations.

If gas in the bulge region was exhausted quickly as suggested above, then *n*-body models can be used to follow its later evolution. Starting from an exponential stellar disc, these models develop an instability that forms a bar, which then buckles into a boxy-peanut structure. Such simulations can also account for observed vertical metallicity gradients, by assuming that the initial axisymmetric disc had a radial metallicity gradient, or that the disc sees an increase of radial velocity dispersion with time. Thus the older and more metal-poor stars in the disc, which are kinematically hotter at the time of the bar formation, turn into a weaker bar and become a vertically thicker box. Stars born later are more metal-rich and radially cooler and form a strong bar, which is vertically thin and peanut-shaped.

If there were no exchanges between the disc-turned-bulge, and the later disc, then the bulge and disc might have stars with different age and chemical properties. On the other hand, abundances might be similar, if the later disc was formed out of pristine gas and experienced rapid SFR.

According to Debattista et al. (2019), the bar cannot have formed later than $z = 0.33$, so this event must have happened between 10 Gyr and 3.7 Gyr ago. An interesting endeavour would then be to look for the time/redshift when the first bars are seen.

Demographics

Almost one hundred participants attended (see Figure 1), from 19 countries, with Chile representing the largest fraction (34%). The second-largest population came from the USA (11%), followed by Germany, Brazil, Italy, and South Korea. Attendees from other countries represented 26% of the total; 32% of the participants were female, and a healthy 50% were young researchers (graduate students or post-docs).

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The success of the conference was largely due to the efforts of the Local Organising Committee, and in particular María Eugenia Gómez, Paulina Jirón, Cesar Muñoz, Doug Geisler, and Joyce Pullen; most of the Local Organising Committee members are shown at the kickoff meeting in Figure 2. Ivo Saviane would also like to thank all of the speakers who provided their slides.

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Links

[1] Zenodo collection of talks: https://zenodo.org/communities/galacticbulge2018
[2] Conference programme: http://www.eso.org/sci/meetings/2018/gbx2018/program.html

Note

[a] Recommended reading: *Galactic Bulges*, in Astrophysics and Space Science Library, 418, ed. Laurikainen, R., Peletier, R. & Gadotti, D., (Switzerland: Springer).

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Report on the ESO Workshop

The La Silla Observatory — From Inauguration to the Future

held at Universidad de La Serena, Chile, 25–29 March 2019

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This five-day workshop celebrated the achievements of ESO's first observatory, La Silla, on the occasion of its 50th anniversary. La Silla, officially inaugurated on 25 March 1969, was the culmination of the vision of European astronomers to create a major observatory in the southern hemisphere. In the following decades, La Silla served as a testbed enabling the development of scientific, technical and operational expertise in the European astronomical community, establishing communication — channels with the public at large, and working to increase interaction and collaboration with the host country Chile as well as with other astronomical facilities in the Andes mountains. Today, La Silla continues to serve as a superb site hosting the ESO 3.6-metre and NTT telescopes, as well as a number of community-led experiments.

Introduction

La Silla was the main observational resource of European astronomers in the southern hemisphere for the first three decades of ESO's existence. The observatory's many telescopes, with a range of different apertures, provided the tools to drive many discoveries. La Silla was also the testbed for innovations in telescope and instrument technology. The 2.2-metre Max-Planck-Gesellschaft (MPG) telescope with its simple dome and, of course, the many new features implemented in the New Technology Telescope (NTT) in 1989 were critical for ESO's path towards the Very Large Telescope (VLT). Many new instrument concepts were brought to the La Silla telescopes. The focal reducer spectrograph was first introduced with the ESO Faint Object Spectrograph and Camera (EFOSC) instruments and it was copied with the FOcal Reducer/low-dispersion Spectrograph (FORS) instrument on the VLT and at many other observatories. Infrared instruments made gigantic steps over La Silla's history, from single-pixel detectors to the large arrays in use today. La Silla also experienced the transition from photographic plates and simple electronic detectors to charge-coupled devices (CCDs) and today's infrared arrays. La Silla also hosted the first large submillimetre dish in the southern hemisphere. Different operational schemes were tested at La Silla; some new adventures in running observatories included remote observing with the NTT and the Coudé Auxiliary Telescope (CAT), and
the introduction of service observing at the NTT.

The workshop celebrated the scientific, technological, operational and societal achievements over the past half century and charted the possible futures of 4-metre-class telescopes in the era of extremely large telescopes. Many workshop participants had personally experienced and participated in the history of the La Silla Observatory. Their reports reminisced on the remarkable changes in our understanding of the Universe, galaxies, stars and planets. At the same time, the workshop also attracted many young people who presented newer results and their visions for possible future uses of the La Silla telescopes.

The workshop took place in the special auditorium called El Pentagono on the campus of the Universidad La Serena (ULS). The site overlooks the city of La Serena and the bay of Coquimbo, which offered a spectacular setting for the workshop. The conference dinner was at La Silla and included a tour of the observatory.

Workshop overview

The workshop programme was built around five topics: history, science, hosted projects, the future, and contributed talks[1]. These topics were interspersed throughout the workshop so that every day covered several aspects. Hosted Projects — formerly called "National Telescopes" — are telescopes and experiments installed on La Silla that are operated by universities or consortia.

History

The workshop opened with welcome addresses by the Rector of Universidad de La Serena (ULS) Nibaldo Avilés Pizarro, by Mayor of the Higuera municipality Yerko Galleguillos, and by President of the ESO Council Willy Benz. Also in attendance were Vice-Dean of Research and Development of ULS Eduardo Notte, and Director of Research and Development of ULS Sergio Torres.

The historical context of astronomical observatories in Chile was given by Bárbara Silva from the Pontificia Universidad Católica de Chile. The earliest astronomical site explorations by US astronomers were carried out around the end of the 19th and the beginning of the 20th centuries and identified the Atacama Desert around Copiapó and north of La Serena as potentially excellent sites for nighttime observations. The International Geophysical Year in 1958 brought the Chilean sites to the attention of American astronomers again and site explorations by Jürgen Stock — originally for the University of Chicago and later for the Association of Universities for Research in Astronomy (AURA) — identified mountains around Vicuña as possible observatory sites. After the US National Science Foundation selected Cerro Tololo as their southern station, ESO also became interested (through Stock's former advisor Otto Heckmann, then ESO Director General). This was a rather abrupt change from the original plan to place the ESO observatory in southern Africa. Within a few years the La Silla mountain was selected and developed. Silva finished her presentation by displaying a stamp showing the ESO 1-metre telescope, which was issued by the Chilean Postal Office in 1973.

The relationship between Chile and ESO was explored by Claudio Melo, stressing the friendly spirit that has guided this relationship over the years. Chilean astronomy has expanded tremendously over the past few decades and has made the country one of the leading nations in astronomical research.

Relations between the various observatories in Chile were described by Mario Hamuy and Leopoldo Infante. Hamuy has worked extensively at the Cerro Tololo Inter-American Observatory and is a professor at the Universidad de Chile. A leader of a Chilean Millenium project, he was recently head of the Chilean science foundation (Comisión Nacional de Investigación Científica y Tecnológica, CONICYT), and as of October 2019 he is the representative of the Association of Universities for Research in Astronomy (AURA) in Chile. Leopoldo Infante is the director of the Las Campanas Observatory. They stressed the friendly competition between the observatories, but also the assistance they have provided each other, for example, the loan of the first CCD detector from Cerro Tololo to La Silla.

The friendly challenge of the "observatory olympics" is held every few years, featuring competitions in various sports. Doug Geisler reminded the audience of the joint workshops held by the observatories. Several memorable meetings could be reported (for example, the structure of the Milky Way, Galaxy Bulges, SN 1987A). A common concern of all observatories is light pollution; for example, the new illumination of the Panamericana near La Frontera leads to light pollution at the La Silla and Las Campanas observatories. Guillermo Blanc reported on the efforts undertaken by the Oficina de Proteccíon de la Calidad del Cielo del Norte de Chile (OPCC), a collaboration of the observatories and the Sociedad Chilena de Astronomía (SOCHIAS) to maintain the dark skies in northern Chile. Sergio Ortolani gave an account of the sky brightness above La Silla and its long-term evolution. He noted that La Silla has a very dark sky at the zenith and a long-term pattern of cloud coverage. About 70% of nights on La Silla are photometric.

Jorge Melnick began the scientific discussions by offering his list of the top ten results obtained with La Silla telescopes. He first demonstrated the ever-increasing demand for La Silla telescopes by showing the surge in the number of proposals from fewer than 100 at the beginning to nearly 600 proposals for Period 54, before the start of the NTT Big Bang (1995–96) and the introduction of the VLT (1999, Period 63). Results from the early years include many stellar topics, studies of the Magellanic Clouds, the identification of quasar absorbing systems as galaxies and the observation of ultraluminous galaxies. A bibliometric analysis for results published after 1996, when the ESO bibliographic records are complete, lists nearly 6680 published papers based on data from La Silla telescopes until 2018. Among the top results are the discovery of the accelerated expansion of the Universe, the discovery of the peculiar gamma-ray burst GRB 980425/ SN 1998bw, the survey of G dwarf stars to map the solar neighbourhood, tracing the nature of the Galactic centre via the orbits of stars, the connection between host-star metallicity and the probability of hosting a planet, the high fraction of binarity among massive stars, and chemical trends in stars in the thin and thick discs.

The historical development of the ESO telescopes was presented by Massimo Tarenghi, who had participated in the commissioning of the 3.6-metre telescope and led the construction of the 2.2-metre MPG telescope, the NTT and the VLT. He gave an overview of the changing scientific and technical landscapes and the technological advances which led ultimately to the VLT telescopes. Michel Dennefeld gave a first-hand history of some early developments of telescopes and instrumentation. The first large project on La Silla was the Quick Blue Survey, which provided full photographic coverage of the southern sky. The ESO Schmidt Telescope was specifically built for this purpose and Michael Naumann presented some of the original plates. The objective-prism mode of the ESO Schmidt had been used in spectroscopic surveys, for example the Hamburg–ESO Survey, to search for white dwarfs and quasars. Ana Cristina Armond presented new plans to take up objective-prism spectroscopy with the SOuthern Astrophysical Research (SOAR) telescope.

Gerardo Ihle led us on a journey down memory lane, sharing his thoughts about the development of the Mechanical Engineering Group on La Silla; the highlight was the design, manufacture, and commissioning of a new M2 unit for the 3.6-metre telescope, which fixed its image quality issues some 30 years after first light. The La Silla telescopes and instruments were maintained and improved over the years — a critical part of the successful operations. An inside view of the construction of the NTT was given by Sergio Lopriore, who was the project engineer at the time, followed by Jason Spyromilio who recounted stories of the NTT Big Bang, bringing the NTT up to VLT standards. A further legacy of La Silla is the provision of new technologies and Cesare Barbieri charted the path from the NTT to the Telescopio Nazionale Galileo (TNG) on La Palma. Dietrich Baade reported on the impact of remote observing with the NTT, the 2.2-metre MPG telescope and the Coudé Auxiliary Telescope (CAT).

Instrumentation development for La Silla underwent a long and arduous path. Originally, many instruments followed American developments — in some cases copies of successful instruments were purchased. Other instruments were temporarily installed at La Silla telescopes (visitor instruments) to obtain observations of the southern skies. Sandro D'Odorico described how the 2.2-metre MPG telescope and the NTT required new instrumentation that paved the way for many VLT instruments.

The prominent NTT instruments, EFOSC, ESO Multi-Mode Instrument (EMMI), SUperb Seeing Imager (SUSI) and Son of ISAAC (SofI) were important stepping stones. High-resolution spectroscopy has become a strength of La Silla and Luca Pasquini presented its history. The Coudé Echelle Spectrometer (CES) for the 3.6-metre and the CAT was followed by the Cassegrain Echelle Spectrograph (CASPEC) on the 3.6-metre, which was the only high-resolution spectrograph with polarimetric capabilities, as described by Gautier Mathys. Another high-resolution spectrograph, the Fibre-fed Extended Range Optical Spectrograph (FEROS), was initially mounted at the ESO 1.5-metre telescope and then moved to MPG 2.2-metre. HARPS on the 3.6-metre remains a unique facility for measuring accurate radial velocities.

Christian Gouiffes followed the various attempts at high-time-resolution photometry undertaken at La Silla and gave a very nice account of the ESO rejection of a putative pulsar in SN 1987A found at another observatory. New instruments will equip the 3.6-metre telescope (the Near Infra-Red Planet Searcher, NIRPS) and NTT (Son Of X-shooter, SOXS) in connection with large dedications of observing time for powerful surveys of the next decade. Colin Snodgrass also presented a proposal for a high-resolution imager (GravityCAM) for the NTT.

Many infrared instruments debuted at La Silla and Ulli Käufl gave an overview of infrared instrumentation on La Silla over four decades. The first instruments were bolometers, followed by the first spectrographs (IRSPECs) and cameras (IRACs) and the extension into the thermal infrared with the Thermal Infrared MultiMode Instrument (TIMMI) instruments. The most prominent TIMMI result came from following the impact of comet Shoemaker-Levy 9 on Jupiter.

Experiments occasionally came to La Silla, for example the millimetre-wave heterodyne receivers brought to the ESO 1.5-metre and later the 3.6-metre telescopes to measure CO(2–1). Thijs de Graauw took part in these early observations and recounted how they eventually led to ESO's hosting the Swedish–ESO Submillimeter Telescope (SEST) on La Silla. Lars-Åke Nyman presented the many successes of the SEST during its 15 years of operation and its important role as precursor to the current submillimetre telescopes in Chile.

Science

Birgitta Nordstrom presented one of the most successful programmes that used La Silla telescopes, showing how the Geneva–Copenhagen Survey of the Solar Neighbourhood changed our views of the Milky Way. This project, which lasted for over 15 years and required more than 1000 observing nights, collected the space motions of over 14 000 F- and G-type stars within ~ 100 pc (complete out to 40 pc) of the Sun. Distances, absolute magnitudes, effective temperatures, metallicity, proper motions (from the HIPPARCOS satellite) and radial velocities for all the stars were determined. About a third (34%) of the stars are binaries. From these observed values, several quantities (ages, space motion and orbital parameters) were derived. The oldest stars reflect the chemical abundance in the early Universe before chemical enrichment took place.

Figure 1. Conference participants at sunset on La Silla.

Monique Spite gave a historical introduction to the recognition of metal-poor stars and their importance in understanding chemical enrichment. She described the contributions by La Silla telescopes, in particular the searches by the Hamburg–ESO objective-prism survey with the ESO Schmidt telescope and follow-up high-resolution spectroscopy. These studies were continued with one of the first VLT Large Programmes on the "first stars" with the UV-Visual Echelle Spectrograph (UVES). The importance of stellar binarity (and multiplicity) was described by Hans Zinnecker. The ever-improving image quality led to the "breaking up" of the most massive known stars into smaller constituents and the La Silla telescopes played an important role, particularly in resolving the stars in the Tarantula Nebula. Similarly, the young stars in the Orion star formation region are mostly binaries, and it has since become clear that nearly all massive stars are in close binaries.

Michel Mayor, the guiding light behind the High Accuracy Radial velocity Planet Searcher (HARPS), presented the evolution of exoplanet discoveries with this instrument. Later in the year, Michel received (together with Didier Queloz) half of the 2019 Nobel Prize in Physics for essentially founding the field of exoplanet research as it is conducted today. The dedication of a large fraction of observing time over nearly two decades, coupled with the exquisite wavelength accuracy of HARPS, has contributed to the field's progressing from the discovery of gaseous giant planets to finding rocky super earths and uncovering several planetary systems. Radial velocity searches have been performed over many years with the (hosted) Euler telescope and Stéphane Udry described the many successes. By now, planets with orbits of longer than 10 000 days (> 27 years!) have been found. Francesco Pepe charted the successes of HARPS and how it is now part of a suite of instruments used to study exoplanets. The prospects for this field are bright, with NIRPS on the 3.6-metre opening up the possibility to search for planets around low-mass stars, as presented by Francois Bouchy. Thierry Forveille (on behalf of Xavier Bonfils) showed how small telescope projects, like the three robotic ExTrA hosted telescopes on La Silla, can be used to search for transiting planets around M dwarfs and to study their atmospheres. A similar project focusing on the brightest stars is the Multi-site All-Sky CAmeRA (MASCARA), which is run by Ignas Snellen.

André Maeder presented La Silla's contributions to stellar astrophysics. HARPS has become the instrument of choice for determining stellar abundances and collecting the time series spectra required for asteroseismology. Combined with theoretical progress on modelling rotating stars, our understanding of the interiors of stars has increased dramatically. The observations of globular clusters have always been central to stellar evolution studies and Georges Meylan summarised what is known about cluster kinematics and dynamics. The line of instruments from CORAVEL (Danish 1.5-metre telescope) to CORALIE (Euler 1-metre telescope) and to HARPS at the 3.6-metre with ever increasing radial velocity accuracy was leading the way to resolved kinematics and dynamics in globular clusters.

Frank Eisenhauer summarised 28 years of observations of the Galactic centre from La Silla and Paranal, culminating in the spectacular observations of the effects of strong gravity close to the supermassive black hole at the centre of the Milky Way. La Silla telescopes were among the first to employ speckle imaging (for example, the SHARP camera) and adaptive-optics-assisted observations of the stellar population in the densest part of our Milky Way. Tracing the orbit of the star S2 around the black hole commenced at La Silla.

Cataclysmic variables and the current status of white dwarf observations were presented by Linda Schmidtobreick and Tom Marsh, respectively. La Silla telescopes have contributed to these fields via numerous Target of Opportunity (ToO) and monitoring programmes. UltraCAM is a visitor instrument which provides unique high-time-resolution capabilities helpful for many of the white dwarf studies. One of the primary goals of SOXS is the monitoring of variable sources. Pietro Schipani presented the concept and goals of SOXS. The wide-band spectroscopic coverage and the large allocation of observing time at the NTT will enable surveys of transient phenomena on an unprecedented scale. SOXS follows in the footsteps of the Public ESO Spectroscopic Survey of Transient Objects (PESSTO), which has provided new insights into supernovae and gamma-ray bursts (GRBs). PESSTO and its successor ePESSTO were presented by Rubina Kotak. PESSTO followed a long tradition of programmes studying supernovae at La Silla. Masimo Turatto was a key member of those projects and summarised the many results on supernovae obtained with La Silla telescopes. A special aspect he emphasised is the important role of such programmes in forming European collaborations.

SN 1987A has a special place in La Silla's history. The observations and unique contributions by the La Silla telescopes were summarised by Patrice Bouchet. The early indication of circumstellar material stemmed from NTT observations and was later confirmed by HST. The infrared observations of SN 1987A were led by ESO facilities and they provided important results, including monitoring the early dust formation and freeze-out at late times. An unbroken observational record of SN 1987A exists until today and continues with the inclusion of VLT and ALMA.

The Galactic bulge has been a favourite target for La Silla telescopes. Beatriz Barbuy reported on the latest results. The old population of the bulge has been confirmed and a clear signal of enrichment of alpha elements by core-collapse supernovae is found. The abundances in the bulge are comparable to those in the thick disc, while the oldest globular clusters are confined to the bar in the inner Galaxy.

Hosted telescopes

La Silla has hosted non-ESO ("national") telescopes for many years. Some of these operated on a mixed model with observing time available to the ESO community. The Danish 1.5-metre telescope began operating in 1978 and Michael Andersen gave an overview of its scientific achievements as well as future plans. This telescope was also one of the first on La Silla to use a CCD detector. This setup was used by a Danish team to discover the first distant supernovae, which opened up the possibility of observing the cosmic expansion rate beyond the local Universe. In addition, the telescope has also made important observations of GRBs and lensing of exoplanets. Today the Danish 1.5-metre is fully dedicated to photometry and is jointly operated by a Danish and Czech consortium. It is regularly used for exoplanet transit observations, and also discovered the rings around the asteroid Chariklo via occultations.

One of the first robotic telescopes was TAROT (Télescope à Action Rapide pour les Objets Transitoires — Rapid Action Telescope for Transient Objects), designed to hunt for GRBs; this project was presented by Michel Boër. The REM (Rapid Eye Mount) robotic telescope was installed in 2003 to follow GRBs photometrically in the infrared. Emilio Molinari presented the history and successes of this telescope. Today, REM focuses on time-domain astronomy (mostly follow-up of fast triggers like GRBs and kilonovae) but also exoplanet transits and space debris. The TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST) is a robotic 60-cm telescope and was presented by Emanuel Jehin. TRAPPIST-South has now operated for 10 years and is also used for educational purposes in university courses. Its biggest success so far is the discovery of a planetary system consisting of seven transiting Earth-like planets around an ultra-cool dwarf (2MASS J23062928-0502285, now better known as TRAPPIST-1). This is one of the richest and best studied planetary systems so far.

After many years of time being offered to the ESO community on the MPG 2.2-metre telescope, the telescope has now become a hosted telescope on La Silla and is operated by the MPG. The exciting prospects of the BlackGEM telescope array were presented by Paul Groot. The three 60-cm telescopes are mainly set up to observe the electromagnetic counterparts of gravitational wave events. The installation is well under way and first light was obtained in January 2020. Another future telescope is the ESA TestBed Telescope (TBT), a 1-metre telescope to continuously monitor the sky for space debris and near-Earth objects. It will be a precursor to the ESA Near Earth Object Survey Telescope (NEOSTel) to survey the sky continuously in order to detect fast-moving objects.

The first La Silla telescope, the 1-metre photometric telescope, was installed in 1966 (even before the official inauguration of the observatory) and, as presented by Moni Bidin, since it ceased ESO operations it has been used by Bochum University and the Universidad Católica del Norte. A new high-resolution spectrograph (FIDEOS) built by the Pontificia Universidad Católica de Santiago was installed in 2016 and is used for exoplanet work. An important aspect of small (privately-run) telescopes is the training of astronomers at the start of their careers. Alessandro Ederoclite described the potential use of small telescopes in the future. Throughout its history, La Silla has often served as the first introduction to professional astronomy for early career researchers, and more recently this role has been boosted as the site of several astronomy training schools. Bruno Dias gave an account of the most recent school and Michel Dennefeld placed this into the wider context of the Network of European Observatories in the North (NEON) schools.

Future

The workshop ended with a general discussion of the future of La Silla. Andreas Kaufer gave an overview of the plans for the next few years to set the stage of the discussion. Central to these are the operation of the 3.6-metre telescope and the NTT, which will be equipped with new instruments that will be dedicated to specific science topics. Once the 3.6-metre telescope has been equipped with HARPS and NIRPS, it will become the primary facility for high-precision radial velocity studies in the optical and the near-infrared. SOXS on the NTT will focus mainly on the spectroscopy of transient objects and will be the primary spectroscopic follow-up facility for future surveys. A third component is the hosting of telescopes run by external consortia to enable access to the southern hemisphere at an excellent site.

During the discussions a number of points were made. La Silla telescopes already complement the current flagship facilities, VLT and ALMA, and will become workhorses for massive surveys of the brighter sky, targeting all objects that do not require 8-metre- or 40-metre-class telescopes. The time domain will become a major area for 4-metre-class telescopes in the future. Many science cases requiring long-term monitoring (for example, exoplanets, transient phenomena) will be best served with ESO’s 4-metre-class telescopes. The support role of some of these telescopes to complement missions such as PLATO was also stressed several times.

Demographics

The workshop was attended by 74 registered participants (see Figure 1), with only nine female participants (just under 12%). This was lower than the ratio of women to men in the Science Organising Committee (3:9). There were only five women among the 41 invited speakers (also 12%). Of the 18 contributed talks only 2 were given by female speakers. It should, however, be noted that more than half of the participating women were invited speakers. These numbers reflect in part the demographics during the early history of astronomy in Europe.

Summary

The La Silla Observatory has participated in most of the revolutions in astronomy over the past 50 years. The synergies with other observatories, in particular with space-based observations in the ultraviolet, in X-rays and in gamma rays, have been highly beneficial. The development of state-of-the-art instrumentation and the improvement in detector technologies reduced the need for larger telescopes for several decades. A further strength of La Silla programmes was (and still is) the large instrument complement and the possibility to execute long-term programmes — in some cases lasting decades. La Silla has been Europe’s flagship facility for three decades and has continued to produce exciting science results from surveys during the VLT era. In the future, it will focus its facilities even more on long-term and survey projects, which are impossible at larger telescopes given the demands on their time.

La Silla telescopes cover an important part of ESO’s integrated observing system as offered to its community. The La Silla observatory offers a prime site, significant instrumental capabilities and a versatile operations model. Fifty years after its inauguration the La Silla Observatory is still going strong and the promise of new scientific discoveries continues.

Acknowledgements

The organisers would like to thank the University of La Serena for the support provided for this workshop.

Links

[1] The programme with links to the individual presentations: https://www.eso.org/sci/meetings/2019/lasilla2019/program.html

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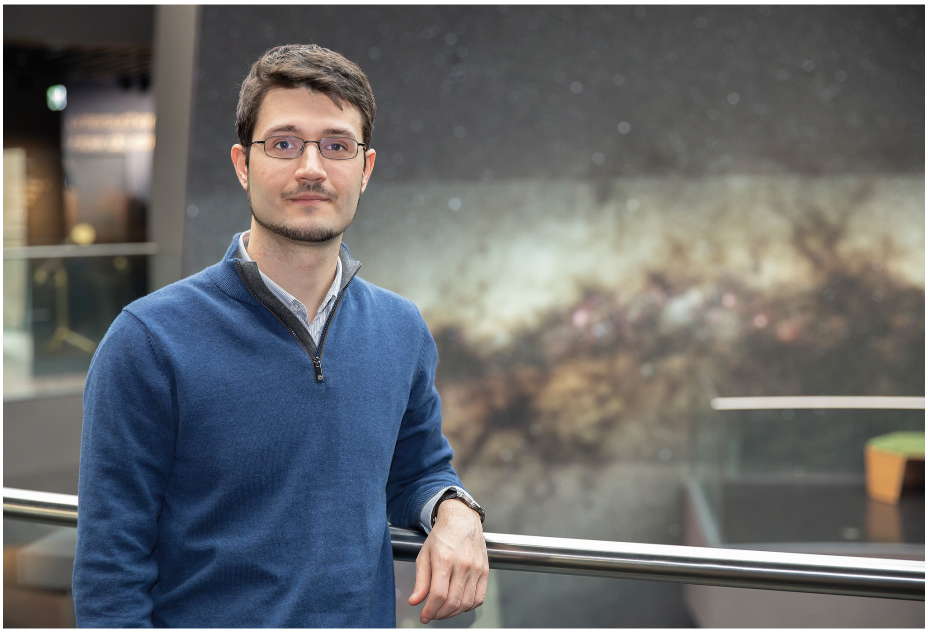
Fellows at ESO

Francesco Belfiore



The light is different in the Atacama Desert. I will never forget the colours of the sunset driving down the road leading away from the Atacama Large Millimeter/submillimeter Array (ALMA), after a busy day's work attaching cables to electronics boxes in a crammed space at the back of the Atacama Pathfinder EXperiment (APEX) telescope. Hosted on the Chajnantor plateau, at an elevation of around 5100 m above sea level and right next to ALMA, the APEX telescope is a small island of state-of-the-art astronomical equipment in the middle of a seemingly Martian landscape.

As an ESO fellow I spend part of my functional duty time as support astronomer for APEX. This experience has allowed me to perform a wide variety of observations for scientists from different ESO Member States, but also given me first-hand experience of the challenges involved in running a world-class observatory — including the mild dizziness associated with working at more than 5000 m above sea level.

I came to astronomy by an indirect route. At school I liked both acting and mathematics. I am still fascinated by the storytelling aspect of performing in plays and the adrenaline rush of walking onto a stage. As for mathematics, I admire the logical constructs of Euclidean geometry, which one of my teachers in high school in Catania, Sicily, was particularly good at presenting. Aged 16 I was awarded a full scholarship to attend the United World College of the Adriatic[1], an international residential high school in Duino, Trieste. In Duino I had my first encounter with experimental science in a well-stocked chemistry lab. To my chemistry teacher Anne Brearley I owe my decision to apply to read Natural Sciences at the University of Cambridge in the UK.

I loved the undergraduate courses and the student experience in Cambridge. I specialised in physics and mostly enjoyed the theoretical physics courses. For my masters thesis I approached Paul Alexander, who guided me through a theoretical study of the 21-centimetre atomic hydrogen signal from cosmic reionisation. I greatly enjoyed the work, which brought together so many different aspects of the physics, from quantum mechanics to cosmology. I felt, however, that I was missing the thrill that comes from experimental verification. I therefore applied for a PhD in observational astronomy. I have to thank my PhD advisor, Roberto Maiolino, at the Cavendish astrophysics group in Cambridge, for giving me the chance to meet this challenge head on.

Even in the first few months of my PhD, Roberto gave me a great amount of freedom to pursue my own ideas and encouraged me to get involved in MaNGA (Mapping Nearby Galaxies at APO — APO is the Apache Point Observatory), a large international collaboration with several key members based in the USA. The collaboration has been using the Sloan Digital Sky Survey (SDSS) 2.5-metre telescope to conduct an unprecedented survey of nearby galaxies with integral-field spectroscopy. Joining the SDSS-MaNGA collaboration was a defining event in my professional career. I got involved in many aspects of the survey, from planning and data analysis, exploring the first datasets, writing technical documentation and organising activities for early career researchers joining the collaboration. My work was scrutinised by people other than my advisor, and sometimes strongly criticised, in regular meetings and telecons. Most of what I know about observational astronomy I owe to the fantastic group of people in MaNGA.

From the time of my PhD, my work has been dedicated to studying the chemical make-up of galaxies to draw conclusions about their origins and evolution. My PhD advisor was instrumental in my long-term interest in the physics of the interstellar medium. I am also grateful to Francesca Matteucci and Fiorenzo Vincenzo for introducing me to the beauty of chemical evolution modelling. The appreciation of this theoretical framework has given me insight and motivation for my observational work. The long-term goal of my research is to trace the history of how disc galaxies assembled by tying their star-formation histories with their current and past chemical abundances.

After seven and a half years as a student in Cambridge I was keenly aware that I needed to expand my academic horizons. When Kevin Bundy, the Principal Investigator of the MaNGA survey, offered me a job at the University of California, Santa Cruz (USA), I happily accepted. In November 2018 I moved back to Europe and arrived at ESO as a new fellow. I immediately felt that I was no longer just a postdoc, but a valued member of the observatory team and of the scientific community in Garching. I wanted my time at ESO to be a learning experience and a time to expand my skill set. I therefore decided to split my functional duty time between outreach at the ESO Supernova Planetarium & Visitor Centre and working as an APEX support astronomer. I had extremely limited experience of submillimetre astronomy before taking the job at APEX, but Carlos de Breuck and Palle Møller gave me a crash course during my first time in Chile. Overall, ESO combines many of the aspects I most enjoy about doing astronomy: an open and international environment, an amazing group of peers, and the ability to draw direct links between ideas, instruments and observations.

Links

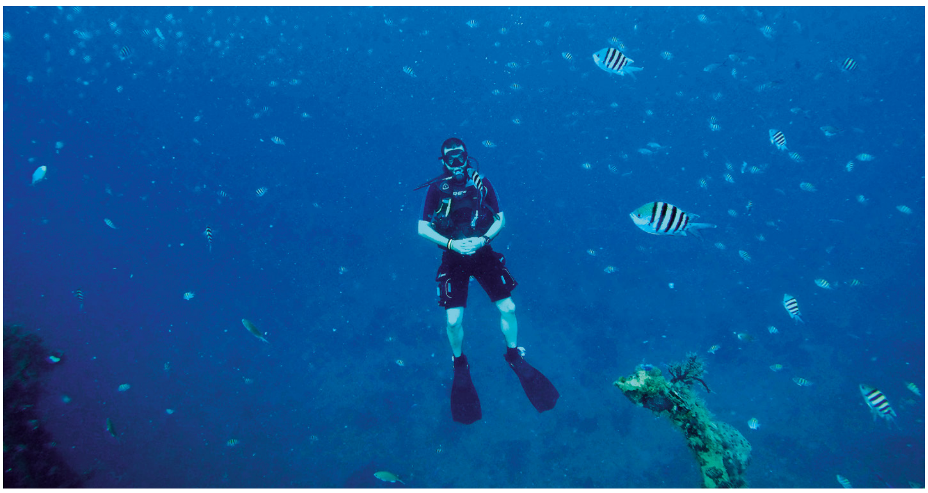
[1] The United World College of the Adriatic: https://www.uwcad.it/

Romain Thomas

I have always been curious. Since I was a kid, I have always loved to try to understand how things "work". That's why I have always liked science in general and physics in particular. However, unlike some of my colleagues, the astronomy direction came later when I was a young adult.

After my high-school diploma, I went to preparatory classes in physics and technology for two years (*classes préparatoires* in the French system). These years are generally preparation for engineering schools, and include a heavy load of physics, mathematics, and in my case, engineering science. It is during these years that I started to consider doing research in fundamental science. After these two years, I enrolled in the magistère of fundamental physics at the Université Paris-Sud during the last year of my bachelor degree. It is at that moment that I started to become interested in astronomy, at first from a theoretical point of view in the fields of cosmology and general relativity. During my masters degree, I enrolled in all the available astrophysics classes. It started to become a passion for me, which is why I spent two internships at the University of La Plata in Argentina to work on black hole entropy and co-authored my first paper!

After two years of masters work, I started a PhD with Olivier Le Fèvre in the Laboratoire d'Astrophyque de Marseille (LAM) to work on an ongoing high-redshift galaxy survey, the VIMOS Ultra Deep Survey (VUDS). The thesis aimed to study when galaxies are born. Those 3+ years were a challenge, composed of periods of success, some failures and a lot of sleepless nights. I really enjoyed it because this was really about trying to understand what we see in the sky and why it appears as it does. I learnt a lot about data processing and how to do scientific analysis. I have always been amazed by how many different science areas you can address using the same sample of objects and how you can connect them. It is also where I discovered another passion, software development. I learned how to use and write code, and since then I have never stopped.



Romain Thomas

From a more personal point of view, this experience was also amazing. The large team working on this project involved people from very different cultures. It made me appreciate working in such an environment and I wanted to continue. After my PhD I flew to Chile, to the University of Valparaiso, for a two-year postdoctoral position. During these two years, I joined the collaboration of another high-redshift galaxy survey, VANDELS. This collaboration allowed me to go for the first time to the Very Large Telescope (VLT) to observe with the VIsible Multi Object Spectrograph (VIMOS), which is now decommissioned. This first contact with Paranal was like a dream. I completely fell in love with the observatory, and I realised this is the kind of place I want to work in. So I applied for an ESO fellowship and got accepted!

I have been at ESO for almost three years now, and it has been the most thrilling experience I could ever dream of. As an ESO fellow, I have 80 days/nights as a support astronomer, which results in, on average, one shift per month. I am always excited to go to the observatory. The first few months are not easy because there is a lot to learn and to remember but carrying out the observations is really exciting. I always wonder, when looking at the data we gather, what people will make of them. Our work is also to make sure that these data or of the best quality. I am now support astronomer of both UT1 (Antu) and UT2 (Kueyen), which mainly use spectrographic instruments. In parallel with core operational duties, I am leading a team writing a system for data visualisation called SCUBA. It is the first time that I have been in charge of such a large project and has very much helped me to understand how the Paranal system and how each instrument work. The most challenging part of this fellowship is to keep up with the science. In the beginning, it is easy to get "swallowed up" by the duty side of the work, but that becomes easier over time. I am also fortunate to be involved in extensive collaborations, which definitely prevent me from losing track of that aspect.

Camila Navarrete

You might think that my decision to be an astronomer was straightforward, being Chilean, and with Chile being the focal point of a huge fraction of the current telescope light collecting area worldwide. Nevertheless, during my childhood I had never heard of astronomy as a potential professional career. And having grown up in Santiago — the capital of Chile — I could never appreciate the night sky. Although ever since I can remember I was always really fascinated by physics. I enjoyed the challenge of solving a physics problem, identifying the different forces involved, solving equations and then predicting what was going to happen to the object of study as a result.

I remember my physics teacher at high school was extremely demanding, sometimes asking us to solve problems that were closer to university level. Instead of feeling overwhelmed by this, I felt encouraged to solve these problems, even looking for higher-level textbooks with my friends. One year before finishing high school education I hadn't decided what to do next — possibilities included engineering in physics, or a bachelor's degree in physics or even literature. I had always loved reading novels and the classics, and that was also a secret option at that time.

During the summer holidays before my last year of high school, I heard in the news that the best students in Chile were choosing astronomy as a career. My first reaction was of incredulity and then of curiosity. Why astronomy? I didn't have any education in astronomy in school, so I decided to enroll in a month-long summer school in astronomy directed by the University of Chile. Frankly, I really just wanted to know what astronomy was about. The campus was near my house and the classes were just 1.5 hours in length every afternoon, so it wasn't a huge sacrifice of my last summer holidays as a high-school student. After the first classes, I was amazed. Why hadn't I known about all of these applications of the laws of physics before? After four weeks and one visit to the local university observatory, I had decided. I wanted to become an astronomer.

I was so determined to do astronomy that I chose a bachelor's degree in astronomy at the Pontificia Universidad Católica de Chile, which at that time was the only university in Santiago with direct access to that field. After four years of classes, I was most interested in stellar astronomy, stellar interiors and variable stars. I started to work on my bachelor thesis studying Δ Scuti low-amplitude variable stars in three open clusters, using infrared observations. To find variable stars, several images of the same area have to be collected in order to recover the stellar light variations over time. My first study was completely disappointing as I couldn't recover any variability despite some of the stars in the cluster being known to be variable. But that was not really surprising, variable stars tend to have smaller variations in the infrared compared to the optical, where most of the variables have been discovered so far.

After finishing my bachelor's degree, I started the master's programme at my former university. At that time, in 2011, my plans were absolutely defined — I would do the two years of a master's and then start to apply to do a PhD abroad. During my master's I decided to do a similar but much more challenging project; I used several near-infrared observations from the Visible and Infrared Survey Telescope for Astronomy (VISTA) at Paranal to find and characterise the variable star population of the biggest globular cluster in the Milky Way, Omega Centauri. This cluster hosts more than 500 known variable stars of different types, including some of the best distance indicators we have in astronomy. In my master's thesis I recovered the variability of more than 300 variables in infrared bands, comparing their amplitude with the amplitude of variability in the optical and deriving a very precise distance to Omega Centauri using the period-luminosity relation. This relation — first discovered by Henrietta Swan-Leavitt — relates the period of the pulsation to the absolute magnitude of the star and is found in all pulsating stars. When observing a variable, you can measure its apparent magnitude, and by monitoring the variability of the star over time you can measure its period, thus precisely estimating its distance using the period-luminosity relation.

My decision to do a PhD abroad changed completely after I became the mother of a wonderful daughter. I decided to do the PhD at the same institution, but while my daughter was still small, I took the opportunity to spend several months abroad doing part of my research at the Institute of Astronomy at the University of Cambridge as part of a big collaboration aiming to study the stellar halo of the Milky Way.

My PhD thesis was dedicated to studying the stellar streams and overdensities present in this halo, observable from the southern hemisphere. These stellar substructures are relics of past accretion events from the formation history of the Milky Way. Most of the previously known stellar substructures were discovered from the north, while the southern sky remained relatively unexplored. In my thesis, I explored data collected by wide-field photometric surveys, like ATLAS, the ESO Public Survey carried out by the VLT Survey Telescope (VST), as well as variability and deep photometric surveys. I also proposed my own spectroscopic observations to detect, confirm and characterise several known and new stellar streams populating the southern skies, particularly around the Magellanic Clouds — the biggest satellite galaxies of our Galaxy, which also contain their own stellar substructure.

Choosing ESO was an easy decision, except for the fact that it is located in Santiago, where I have been for all of my career so far. Nonetheless, interacting with frequent visitors from all over the world, and working with colleagues from many countries, it is easy to forget that I am still in my home town. At ESO, I split my time between my own research, some outreach activities in Spanish for school students, and my duties at the VLT. There, I work as a support astronomer at the UT2 (Kueyen) telescope. I execute programmes on behalf of astronomers who want to observe with the Ultraviolet-Visual Echelle Spectrograph (UVES), and the X-shooter and the Fibre Large Array Multi Element Spectrograph (FLAMES), choosing them based on the weather conditions and scientific priorities, and checking in real time the quality of the data we acquire. I also support visiting astronomers who come to Paranal to carry out their observations. Working at Paranal can be tough as it involves night-time work for several nights in a row. However, it really pays off when you can see all the stars embedded in the Milky Way in the spectacular night sky.

Personnel Movements

Arrivals (1 January–31 March 2020)

Europe

Brazil, Fiona (UK)	Head of Human Resources
Davison, Thomas (UK)	Student
Engler, Byron (NZ)	Student
Héritier, Cédric Taïssir (FR)	Engineering and Technology Research Fellow
Scibior, Pawel (PL)	Electrical Engineer
Wegener, Anna-Lynn (DE)	Head of the Department of Communication

Chile

Arrue, Ricardo (CL)	Telescope Instruments Operator
Dullius Mallmann, Nicolas (BR)	Student
Duran, Carlos (CL)	Apex Station Manager
Houllé, Mathis (FR)	Student
Korhonen, Heidi Helena (FI)	Operations Staff Astronomer
Kundu, Richa (IN)	Student
Lagos, Felipe (CL)	Student
Lizana, Vincente (CL)	Software Engineer
Megevand, Vincent (CH)	Telescope Instruments Operator
Messias, Hugo (PT)	Astronomer
Montes, Vanessa (CL)	Systems Engineer
Pessi, Priscila (AR)	Student
Ramirez, Christian (CL)	Optical Coating Engineer
Uzundag, Murat (TR)	Student

Departures (1 January–31 March 2020)

Europe

Fiorellino, Eleonora (IT)	Student
Guglielmetti, Fabrizia (IT)	ALMA Pipeline Processing Analyst
Kabátová, Anežka (CZ)	Student

Chile

Abril Ibáñez, Javier (ES)	Student
Alonso, Jaime (CL)	Electronics Engineer
Bartlett, Elizabeth (UK)	Fellow
Ciechanowicz, Miroslaw (PL)	Head of Engineering group
Desbordes, Christine (FR)	Head of Logistics
Leclercq, Julien (FR)	Mechanical Engineer
Reyes, Claudia (CL)	Telescope Instruments Operator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Sangku Kim/ESO

A mirror shows a reflection of one of the telescopes located at La Silla Observatory, with an incredible background view of the Milky Way galaxy and the sunrise.

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