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The Cherenkov Telescope Array Observatory Comes of Age
MOONS: The New Multi-Object Spectrograph for the VLT
The ALPINE–ALMA [CII] Survey

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ESO Headquarters
Karl-Schwarzschild-Straße 2
85748 Garching bei München, Germany
Phone +498932006-0
information@eso.org

The Messenger
Editor: Gaitee A. J. Hussain
Layout, Typesetting, Graphics:
Jutta Boxheimer, Lorenzo Benassi,
Mafalda Martins
Design, Production: Jutta Boxheimer
Editorial Assistant: Isolde Kreutle
Proofreading: Peter Grimley
www.eso.org/messenger/

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Contents

The Organisation

MOONS

Astronomical Science

Astronomical News

Front cover: This image shows the beginning of sunrise over ESO's Observatory. One of the VLT's 8-m Unit Telescopes is visible to the bottom right, illuminated by moonlight. Further in the distance there are two Auxiliary Telescopes pointing upwards. While science operations have been suspended since March 2020 due to the COVID-19 pandemic, the impressive skies are waiting to be explored once it becomes safe to resume regular travel.
Credit: ESO/Nicolas Blind

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The Cherenkov Telescope Array Observatory Comes of Age

Federico Ferrini [1]
Wolfgang Wild [1,2]

[1] CTAO, Heidelberg (DE) and Bologna (IT)
[2] ESO

The Cherenkov Telescope Array (CTA) is the next-generation ground-based observatory for gamma-ray astronomy at very high energies. With up to 120 telescopes on two sites, CTA will be the world's largest and most sensitive high-energy gamma-ray observatory covering the entire sky. It will consist of a northern array located at the Roque de los Muchachos astronomical observatory on the island of La Palma (Spain) and a southern array near the European Southern Observatory site at Paranal (Chile). Three classes of telescope spread over a large area are required to cover all of CTA's very-high-energy range from 20 GeV to 300 TeV.

Conceived around a decade ago by a group of scientists, we are now on the cusp of constructing the largest observatory to study the gamma-ray Universe. Here we present a short look back at the evolution and recent maturation of the CTA project, as well as an outline of our expectations for the near future. A comprehensive introduction to CTA, including the detection technique, its history, the extraordinary improvements with respect to previous experimental facilities, and the scientific objectives has been provided by Werner Hofmann, Spokesperson of the CTA Consortium (Hofmann, 2017).

Conceiving the Cherenkov Telescope Array

Ground-based gamma-ray astronomy is a young field with enormous scientific potential. The possibility of astrophysical measurements at teraelectronvolt (TeV) energies was demonstrated in 1989 with the detection of a clear signal from the Crab nebula above 1 TeV with the Whipple 10-m imaging atmospheric Cherenkov telescope (IACT). Since then, the instrumentation for, and techniques of, astronomy with IACTs have evolved to the extent that a flourishing new scientific discipline has been established, with the detection of more than 150 sources and a major impact in astrophysics — and, more widely, in physics. The current major arrays of IACTs (the High Energy Stereoscopic System [H.E.S.S.], the Major Atmospheric Gamma Imaging Cherenkov Telescope [MAGIC], and the Very Energetic Radiation Imaging Telescope Array System [VERITAS]) have demonstrated the huge potential for studying the physics at these energies as well as the maturity of the detection technique. Many astrophysical source classes have

Figure 1. Distinguished guests and stakeholders in the LST project participate in a traditional Japanese ribbon-cutting ceremony at the inauguration of LST-1 on 10 October 2018.

A. Okumura

CTAO

Figure 2. The CTA Observatory (CTAO) consists of two array site locations — one in Chile and one on La Palma — and three office locations — the CTAO Headquarters (interim) and Science Data Management Centre in Germany and the local office (and future site of the headquarters) in Italy.

been established, some of them now including many well-studied individual objects.

It was a little over a decade ago that a group of scientists first gathered to begin planning the next-generation gamma-ray instrument. And while CTA's instrumentation is very much an evolution of the proven IACT technology of its predecessors, it is vastly expanding the range and scale, enabling us to see the Universe at the highest energies with unprecedented accuracy and sensitivity. This will be accomplished with two arrays (one near ESO's Paranal Observatory in Chile and the other on the island of La Palma, Spain) of up to 120 telescopes of three different types: the Small-Sized Telescope (SST), the Medium-Sized Telescope (MST) and the Large-Sized Telescope (LST).

Between 2008 and 2018, a massive amount of work by collaborations around the world was carried out, both on the scientific and technical fronts. This covered, in particular, the development of the telescope prototypes, cameras and mirrors, and resulted in a virtual menu of finely built operating telescopes for CTA. During this time three different SST designs started to demonstrate their astronomical qualities:

- SST-1M: A single-mirror Davies-Cotton design prototype in Krakow, Poland — from a Czech, Irish, Polish and Swiss collaboration.
- SST-2M GCT: A dual-mirror Schwarzschild-Couder design prototype in Paris, France — from an Australian, Dutch, French, German, and Japanese collaboration.
- SST-2M ASTRI: A dual-mirror Schwarzschild-Couder design prototype on Mount Etna in Italy — from a Brazilian, Italian and South-African collaboration.

The MST prototype is a single-mirror Davies-Cotton telescope installed in Zeuthen, Germany, developed by a large collaboration involving scientists and engineers from Austria, Brazil, the Czech Republic, France, Germany, Italy, Poland, Spain and Switzerland. Meanwhile, an alternative mid-sized prototype, based on the dual-mirror Schwarzschild-Couder design, was conceived and developed by the US, Germany, Italy, Japan and Mexico. A prototype was inaugurated at the Whipple Observatory in Arizona in 2018.

The LST prototype had a different evolution. Conceived and developed by a large collaboration of institutes — from Brazil, Croatia, Germany, France, India, Italy, Japan, Poland, Spain and Sweden — the prototype was constructed on the CTA-North site. The prototype, named LST-1, was inaugurated in 2018 and has since been undergoing commissioning. This is the first telescope to be installed on a CTA site for the moment and, as such, will eventually become the first "champion" of the CTA Observatory (CTAO).

After 12 years of gestation, it is evident that the CTA project is now passing through its adolescent phase; the time has arrived to make final decisions about what the observatory will look like for decades to come. It is now critical to transform all the brilliant ideas into a real observatory that is sustainable, consolidated and easy to maintain in the most cost-effective way. This, in short, is what the present management has been working on since it was installed about two years ago.

Finding the right home

The CTAO has found several locations to call home. Following a CTAO Council decision in 2016, its headquarters will be located in Bologna, Italy, at the Istituto Nazionale di Astrofisica (INAF) premises, in a new building shared with the Bologna University Department of Physics and Astronomy. This decision also made Berlin-Zeuthen the location for the Science Data Management Centre (SDMC) in a new building complex on the Deutsches Elektronen-Synchrotron (DESY) campus. The interim headquarters is located on the Max-Planck-Institut für Kernphysik (MPIK) campus in Heidelberg, Germany.

And to provide access to the entire sky, the CTAO has two array locations: one in the northern hemisphere and another in the southern hemisphere. In July 2015, CTA entered into detailed hosting agreement negotiations with the European Southern Observatory (ESO) for the southern array site near Paranal, Chile, and with the Instituto de Astrofísica de Canarias (IAC) for the northern array site in Villa de Garafía on the island of La Palma in the Canary Islands. The site selections were made after years of careful consideration of extensive studies of the environmental conditions, simulations of the science performance and assessments of construction and operation costs.

CTA's northern hemisphere site is located on the existing site of the IAC's Observatorio del Roque de los Muchachos on the island of La Palma. At an altitude of 2200 m and nestled on a plateau below the rim of an extinct volcanic crater, the site currently hosts the two MAGIC telescopes. The southern site of CTA is 11 km southeast of the location of the Very Large Telescope at ESO's Paranal Observatory in the Atacama Desert, and only 16 km from the construction site of ESO's Extremely Large Telescope.

The road to formalising a hosting agreement with the IAC for the northern site, while intricate — owing to the extensive requirements to integrate the CTA structures into the existing complex of astronomical instrumentation — was relatively short. The agreement was signed in 2016 with the Director of the IAC, taking advantage of the fact that Spain is a shareholder in the CTA project.

For the southern site, the negotiation was more complex, considering the region is a Chilean territory, ESO is responsible for any astronomical infrastructure installed on their land and the Chilean scientific community should benefit from astronomical facilities on their (extraordinary) land. The three negotiations had to be handled in parallel and, thanks to the excellent synergies with the ESO Director General, they were successfully concluded in December 2018. Soon after, the participation of ESO in the CTA project was fully formalised when ESO officially became a shareholder in the CTAO in March 2019.

Getting organised

Building an infrastructure as big and complex as CTA takes a lot of organisation, people and funds, not to mention a governing body that can fully support the diverse and complicated landscape of CTA's multinational investments and business locales.

The CTAO gGmbH, a non-profit limited liability company under German law, *ad interim*, was created in 2014 and is the current legal entity in charge of the preparations to construct the CTAO. However, to manage the construction and then the operation of the CTAO, it will transition to a European Research Infrastructure Consortium (ERIC) as defined by the European Commission. This status will deliver several advantages,

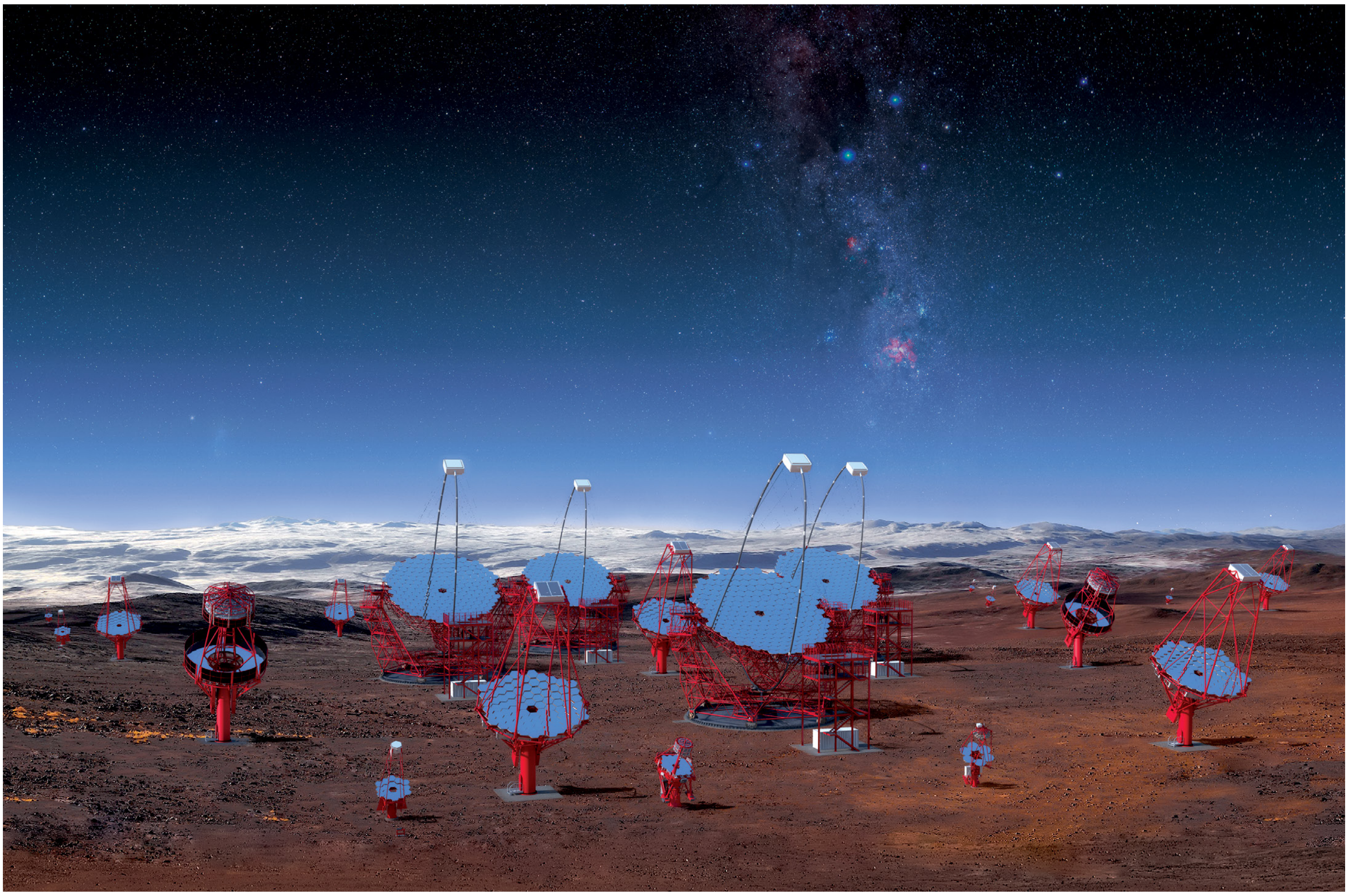
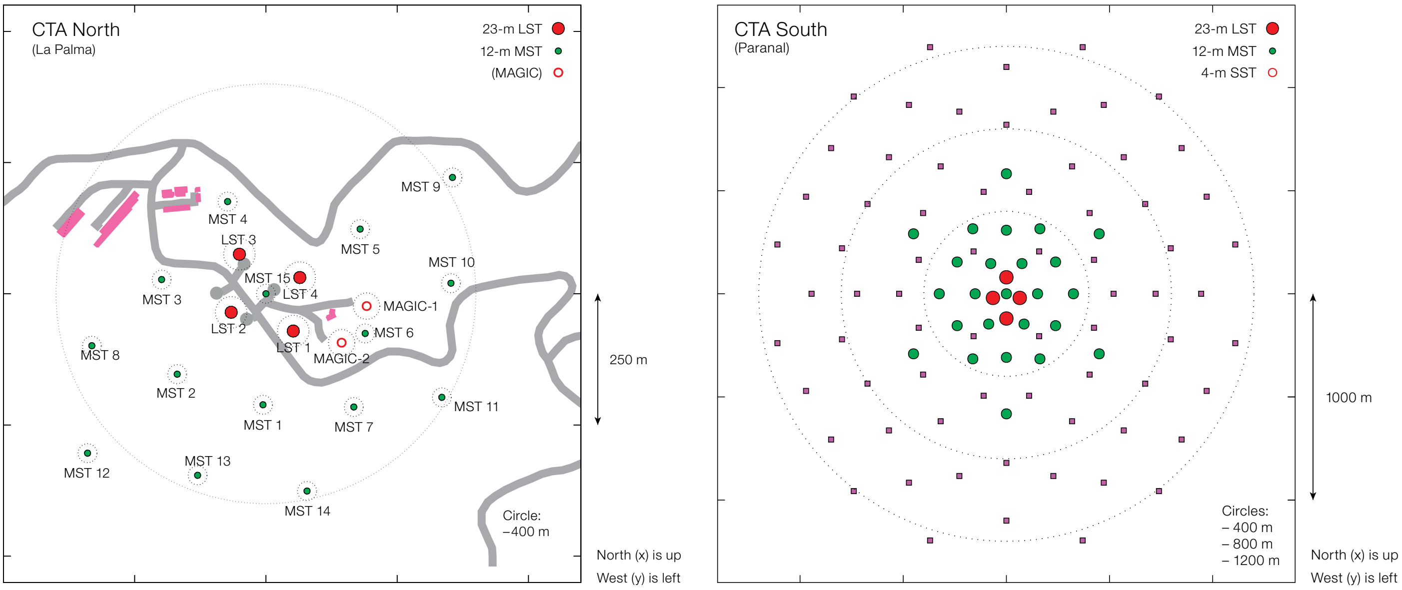


Figure 3. This image illustrates all three classes of the 99 telescopes planned for the southern hemisphere at ESO's Paranal Observatory, as viewed from the centre of the array. This rendering is not an accurate representation of the final array layout, but it illustrates the enormous scale of the CTA telescopes and the array itself.

CTA/M.-A. Besel/IAC (G. P. Diaz)/ESO



Baseline layout: 4 LSTs, 15 MSTs (status: 2017-12-04)

Baseline layout: 4 LSTs, 25 MSTs, 70 SSTs

Figure 4. The site maps for the northern and southern CTAO sites.

from both a political and a financial point of view. The process, led by a Board of Governmental Representatives, toward the application and final recognition of the ERIC status began in the spring of 2018 and, in March 2019, the first part of the application was presented to the European Commission. The process is progressing at a steady pace and we are confident that it will conclude before the end of 2020.

There will be a fundamental consequence of this process: those Members agreeing to participate in the CTAO ERIC will be in a position to unfreeze the funds assigned by their respective governments to the construction of the observatory. A critical constraint to starting construction will start to unravel after the ERIC is in place!

The CTAO is actively preparing for this crucial milestone by finalising the Cost Book (set for approval in June 2020), boosting the CTAO staff (which has more than doubled since 2018, to 37), establishing an administrative structure, preparing the necessary basis for a construction project (for example, construction, safety, integration and verification plans, a unique documentation management system, interface definition and control and software standards), completing system designs for the array sites by the end of 2020 and holding technical reviews, such as Critical Design Reviews, to move from the design phase to the construction phase.

The structure of the CTAO, once the ERIC legal entity is in place, will be organised on four sites: the headquarters in Bologna (Italy), the Science Data Management Centre in Zeuthen (Germany), the CTA-North site on La Palma (Spain) and the CTA-South site near Paranal (Chile).

Strategising and harmonising

As mentioned above, the path from CTA's "adolescence" to full maturity requires a lot of decisions based on funding and the feasibility of execution while not compromising our ability to achieve our exceptional science goals. The full CTA baseline configuration consists of up to 120 telescopes of three types, covering different energy ranges, and distributed over two sites to ensure full sky coverage. Each individual telescope is a functional scientific instrument whose performance can be tested, verified and integrated into a large-scale array consisting of many telescopes.

For widely usable energy coverage, it is desirable for the effective gamma-ray detection area to increase with gamma-ray energy, compensating for the rapid drop of gamma-ray flux with increasing energy (for typical sources, the gamma-ray flux drops with energy, E, like $dN\gamma/dE \sim E^{-2}$ or faster). Hence, rather than deploying one type of Cherenkov telescope on a regular grid, the CTA arrays use a graded approach:

- The lowest energies (20 GeV – 3 TeV) are covered by an arrangement of four 23-m LSTs at each site, capable of detecting gamma rays as low as 20 GeV.
- The middle of the range (80 GeV – 50 TeV) is covered by larger arrays of 25 (CTA-South) and 15 (CTA-North) 12-m MSTs.
- The highest energy gamma rays (1–300 TeV) are detected by a multi-kilometre square array of 70 4-m SSTs in the south.

The small telescopes are only foreseen for the southern array since the highest energies are most relevant for the study of Galactic sources. The use of three different sizes of telescope proved to be the most cost-effective solution, and it allows each telescope type to be optimised for a specific energy range.

Access to the full sky is necessary as many of the phenomena to be studied by CTA are rare and individual objects can be very important. For example, the most promising galaxy cluster, the brightest starburst galaxy and the only known gravitationally lensed TeV source are located in the north. The inner Galaxy and the Galactic centre are key CTA targets and are located in the south.

The baseline configuration foresees 19 telescopes on CTA-North (4 LSTs and 15 MSTs) and 99 on CTA-South (4 LSTs, 25 MSTs and 70 SSTs). However, the present funding situation demands a phased approach, reducing the initial objective to a threshold configuration for the next five years. The optimal distribution of telescopes that is well defined and affordable is the installation of nine telescopes on CTA-North (4 LSTs and 5 MSTs) and between 55 and 65 telescopes on CTA-South (15 MSTs and 40/50 SSTs). The quality of science will be outstanding and far beyond what can be attained with current instruments even in this reduced configuration. The ambitious objective of implementing the full configuration is expected over the following five years.

Overall, CTA is a large science infrastructure with many individual units and a high degree of complexity. There are many good reasons to design and implement the simplest and most harmonised system possible. In fact, a high degree of simplification will be a crucial factor for success, during both construction and operation. This need for harmonisation applies to many subsystems and components of the array. One prominent area concerns the SSTs, where harmonisation is particularly important owing to the large number of units that need to be built, operated and maintained.

Based on the findings and recommendations of a year-long review, and taking into account funding considerations, the CTAO Management formulated its proposal for a unified SST design (called the CTA-SST). The CTA-SST Consortium has now taken responsibility for delivering the SST telescopes based on the ASTRI structure and the Compact High-Energy Camera (CHEC) designs. As for the MST, the newly formed CTA-MST Consortium is proposing a sustainable solution for the provision of telescopes, including structures, cameras and mirrors, for the two sites. Finally, for the LSTs, the situation is more straightforward as only one design exists; their production is being arranged.

Finding CTA's Place in the Multi-messenger Universe

After August 2017, the paradigm for the astronomical world changed and the new mantra is "multi-messenger astronomy". Indeed, the extraordinary sequence which began with a gravitational wave signal, followed after ~ 1.5 seconds by a gamma-ray flash and then by all the electromagnetic detections that could be observed, has modified our approach of studying the sky.

In May 2019, the First CTA Science Symposium "Exploring the High-Energy Universe with CTA" ratified the important role that the CTAO will play in the landscape of new, highly-sensitive observatories becoming operational in the next decade. The CTAO is going to be one of the pillars of multi-messenger astrophysics, which will rely heavily on the detection of gamma rays to pinpoint the sites of activity at extreme energies in the Universe. It will also be the first ground-based gamma-ray observatory open to the worldwide astronomical and particle physics communities as a resource for data from unique, high-energy astronomical observations.

The detection technique adopted by the Cherenkov ground-based telescopes is a perfect integration of frontiers regarding both astronomical and particle physics technologies: the need to reveal a very weak optical signal — just a few photons — within an extremely short timescale — a few nanoseconds — coupled with the best instrumentation from the two branches of physics. This is, at the same time, translated into scientific objectives that are a mixture of unsolved problems for astrophysics and particle physics, spanning the origin of cosmic rays, catastrophic collapse, and the nature of dark matter. Do not underestimate the fact that CTA detectors could reach particle energies some 20 times higher than present CERN collision limits.

The scientific themes that will be the principal objectives of the scientific production of the observatory are summarised. A detailed description can be found in CTA's description of Key Science Projects (CTA Consortium, 2018).

Theme 1 – Understanding the origin and role of relativistic cosmic particles: The existence of highly energetic cosmic particles is known since more than one century. In our Galaxy and beyond, the energy density of such particles is comparable to the energy contained in motions of interstellar gas and in magnetic fields, implying a tight coupling between these carriers of energy in the cosmos and a potentially significant impact of energetic cosmic particles on cosmic evolution. However, a range of basic questions remain:

- *What are the sites of high-energy particle acceleration in the universe?*
- *What are the mechanisms for cosmic particle acceleration?*
- *What role do accelerated particles play in feedback on star formation and galaxy evolution?*

Theme 2 – Probing extreme environments: Acceleration of particles to high energy requires environments of extreme energy density, that are generally characterised by a complex nonlinear interplay of different forms of energy. Very-high-energy (VHE) gamma rays can be used to explore these environments. Gamma rays are also used to probe the other type of extreme environments, the cosmic voids in the space between galaxies. Specific questions concern:

- *What physical processes are at work close to neutron stars and black holes?*
- *What are the characteristics of relativistic jets, winds and explosions?*
- *How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?*

Theme 3 – Exploring frontiers in Physics: VHE gamma rays serve to explore questions of fundamental physics, in scope reaching far beyond astrophysics. Relic particles left over from the Big Bang – such as dark matter particles – can potentially be detected in gamma rays. In their billion-year journey from distant extragalactic sources to Earth, gamma rays furthermore probe subtle effects predicted in many theories, but beyond *the reach of laboratory experiments. Topics addressed include:*

- *What is the nature of dark matter?*
- *How is dark matter distributed?*
- *Are there quantum gravitational effects on photon propagation?*
- *Do axion-like particles exist?*

The investigation of the full spectrum of electromagnetic radiation is going to improve in a dramatic way in the next decades. CTA will cover the highest frequencies on a timescale during which other international projects will start operation: for example, the ELT in the infrared/optical and the Square Kilometre Array (SKA) in the radio. Synergies among the large astronomical infrastructures are going to become the most natural way to develop multi-wavelength and multi-messenger astrophysics; the relationship with ESO instrumentation is obvious now that CTA is an ESO project. The interaction with the SKA has a clear framework since the SKA Organisation and the CTAO signed a Cooperation Agreement, sanctioning their future collaboration in science, technology and management.

In due course, collaboration agreements will be established to make the contribution of this large-scale telescope system as effective as possible in measuring transient phenomena in close coordination with other astrophysical instrumentation, such as gravitational wave interferometers and large-scale neutrino detectors.

Progressing Towards Construction

CTA is currently in pre-construction with some construction activities already begun. While the design and prototyping of subsystems, such as telescopes and cameras, calibration equipment and software elements, are quite advanced, the system-related aspects (for example, system interfaces, an array-wide alarm system and overall integration and verification) are currently being addressed by the CTAO Project Office. At the same time, a simplification of the overall CTA and the harmonisation or choice among different design solutions are being addressed. As previously mentioned, this resulted in a unique SST design for the telescope structure and camera. Other subsystems will undergo a similar exercise.

On the CTA-North site, preparations for the first stage of infrastructure design and construction are well under way for a further three LSTs and the first MST. An agreement between the LST team and the CTAO has been created to provide the framework for CTAO staff to support the LST-1 commissioning and to get better acquainted with the telescope. Moreover, a low-elevation office space has been rented and its refurbishment is being finalised with a local architect.

For CTA-South, the first step in preparing the site is to develop the overall layout of the site's supporting facilities (buildings, power substation, warehouse, etc.) and the required infrastructure, as well as to conduct an analysis of the current telescope positions by marking them in the field and re-evaluating their construction feasibility. The first preparatory procurements (vehicle, generator set, refurbishment of office containers) have been completed or are in preparation. In addition, the road access and the power connection to the public electricity grid are being investigated to find the correct strategy and technical solution. It is the CTAO's intention to begin building the CTA-South access road, data and power connections to the array as soon as the funding becomes available.

Acknowledgements

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Gabriel Pérez Diaz, IAC

An artistic rendering of CTA's northern hemisphere site located on the existing site of the Instituto de Astrofisica de Canarias's (IAC's) Observatorio del Roque de los Muchachos on the island of La Palma. This rendering does not reflect the final layout of the array, but serves to illustrate the scale of the array.

ESO/P. Horalek

The Sun sets behind three of the four Unit Telescopes of the ESO VLT. The first stars are already visible in the cloudless sky.

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MOONS: The New Multi-Object Spectrograph for the VLT

Michele Cirasuolo[1,a]
Alasdair Fairley[2]
Phil Rees[2]
Oscar A. Gonzalez[2]
William Taylor[2]
Roberto Maiolino[3]
Jose Afonso[4]
Chris Evans[2]
Hector Flores[6]
Simon Lilly[5]
Ernesto Oliva[7]
Stephane Paltani[8]
Leonardo Vanzi[9]
Manuel Abreu[4]
Matteo Accardo[1]
Nathan Adams[15]
Domingo Álvarez Méndez[1]
Jean-Philippe Amans[6]
Stergios Amarantidis[4]
Hakim Atek[6]
David Atkinson[2]
Manda Banerji[12]
Joe Barrett[2]
Felipe Barrientos[9]
Franz Bauer[9]
Steven Beard[2]
Clementine Béchet[9]
Andrea Belfiore[11]
Michele Bellazzini[13]
Christophe Benoist[32]
Philip Best[10]
Katia Biazzo[14]
Martin Black[2]
David Boettger[9]
Piercarlo Bonifacio[6]
Rebecca Bowler[15]
Angela Bragaglia[13]
Saskia Brierley[2]
Jarle Brinchmann[16]
Martin Brinkmann[1]
Veronique Buat[17]
Fernando Buitrago[4]
Denis Burgarella[17]
Ben Burningham[18]
David Buscher[3]
Alexandre Cabral[4]
Elisabetta Caffau[6]
Leandro Cardoso[16]
Adam Carnall[10]
Marcella Carollo[5]
Roberto Castillo[1]
Gianluca Castignani[19]
Marco Catelan[9]
Claudia Cicone[20]
Andrea Cimatti[21]
Maria-Rosa L. Cioni[22]
Gisella Clementini[13]
William Cochrane[2]
João Coelho[4]
Miriam Colling[23]
Thierry Contini[24]
Rodrigo Contreras[9]
Ralf Conzelmann[1]
Giovanni Cresci[7]
Mark Cropper[25]
Olga Cucciati[13]
Fergus Cullen[10]
Claudio Cumani[1]
Mirko Curti[3]
Antonio Da Silva[4]
Emanuele Daddi[26]
Emanuele Dalessandro[13]
Francesco Dalessio[14]
Louise Dauvin[9]
George Davidson[2]
Patrick de Laverny[32]
Françoise Delplancke-Ströbele[1]
Gabriella De Lucia[27]
Ciro Del Vecchio[7]
Miroslava Dessauges-Zavadsky[8]
Paola Di Matteo[6]
Herve Dole[28]
Holger Drass[9]
Jim Dunlop[10]
Rolando Dünner[9]
Steve Eales[29]
Richard Ellis[30]
Bruno Enriques[5]
Giles Fasola[6]
Annette Ferguson[10]
Debora Ferruzzi[7]
Martin Fisher[3]
Mauricio Flores[9]
Adriano Fontana[14]
Vincenzo Forchi[1]
Patrick Francois[6]
Paolo Franzetti[11]
Adriana Gargiulo[11]
Bianca Garilli[11]
Julien Gaudemard[6]
Mark Gieles[31]
Gerry Gilmore[3]
Michele Ginolfi[8]
Jean Michel Gomes[16]
Isabelle Guinouard[6]
Pablo Gutierrez[1]
Régis Haigron[6]
François Hammer[6]
Peter Hammersley[1]
Chris Haniff[3]
Chris Harrison[1]
Misha Haywood[6]
Vanessa Hill[32]
Norbert Hubin[1]
Andrew Humphrey[16]
Rodrigo Ibata[33]
Leopoldo Infante[9]
Derek Ives[1]
Rob Ivison[1]
Olaf Iwert[1]
Pascale Jablonka[19]
Gerd Jakob[1]
Matt Jarvis[15]
David King[3]
Jean-Paul Kneib[19]
Philippe Laporte[6]
Andy Lawrence[10]
David Lee[2]
Gianluca Li Causi[35]
Silvio Lorenzoni[4]
Sara Lucatello[34]
Yerco Luco[9]
Alastair Macleod[2]
Manuela Magliocchetti[35]
Laura Magrini[7]
Vincenzo Mainieri[1]
Charles Maire[8]
Filippo Mannucci[7]
Nicolas Martin[33]
Israel Matute[4]
Sophie Maurogordato[32]
Sean McGee[43]
Derek Mcleod[10]
Ross McLure[10]
Richard McMahon[3]
Basile-Thierry Melse[6]
Hugo Messias[4]
Alessio Mucciarelli[21]
Brunella Nisini[14]
Johannes Nix[2]
Peder Norberg[36]
Pascal Oesch[8]
António Oliveira[4]
Livia Origlia[13]
Nelson Padilla[9]
Ralf Palsa[1]
Elena Pancino[7]
Polychronis Papaderos[16]
Ciro Pappalardo[4]
Ian Parry[3]
Luca Pasquini[1]
John Peacock[10]
Fernando Pedichini[14]
Roser Pello[17]
Yingjie Peng[42]
Laura Pentericci[14]
Oliver Pfuhl[1]
Roberto Piazzesi[14]
Dan Popovic[1]
Lucia Pozzetti[13]
Mathieu Puech[6]
Thomas Puzia[9]
Anand Raichoor[19]
Sofia Randich[7]
Alejandra Recio-Blanco[32]
Sandra Reis[4]
Florent Reix[6]

Alvio Renzini[34]
Myriam Rodrigues[6]
Felipe Rojas[9]
Álvaro Rojas-Arriagada[9]
Stefano Rota[11]
Frédéric Royer[6]
Germano Sacco[7]
Ruben Sanchez-Janssen[2]
Nicoletta Sanna[7]
Pedro Santos[4]
Marc Sarzi[44]
Daniel Schaerer[8]
Ricardo Schiavon[37]
Robin Schnell[8]
Mathias Schultheis[32]
Marco Scodeggio[11]
Steve Serjeant[38]
Tzu-Chiang Shen[39]
Charlotte Simmonds[19]
Jonathan Smoker[1]
David Sobral[45]
Michael Sordet[8]
Damien Spérone[19]
Jonathan Strachan[2]
Xiaowei Sun[3]
Mark Swinbank[36]
Graham Tait[2]
Ismael Tereno[4]
Rita Tojeiro[40]
Miguel Torres[9]
Monica Tosi[13]
Andrea Tozzi[7]
Ezequiel Tresiter[9]
Elena Valenti[1]
Álvaro Valenzuela Navarro[9]
Eros Vanzella[13]
Susanna Vergani[6]
Anne Verhamme[19]
Joël Vernet[1]
Cristian Vignali[13]
Jakob Vinther[1]
Lauren Von Dran[41]
Chris Waring[2]
Stephen Watson[2]
Vivienne Wild[40]
Bart Willesme[2]
Brian Woodward[2]
Stijn Wuyts[46]
Yanbin Yang[6]
Gianni Zamorani[13]
Manuela Zoccali[9]
Asa Bluck[3]
James Trussler[3]

[1] ESO
[2] STFC, UK Astronomy Technology Centre, Royal Observatory Edinburgh, UK
[3] Cavendish Laboratory, University of Cambridge, UK
[4] Instituto de Astrofísica e Ciências do Espaço and Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Portugal
[5] Department of Physics, ETH Zurich, Switzerland
[6] GEPI, Observatoire de Paris, PSL University, CNRS, France
[7] INAF-Osservatorio Astrofisico di Arcetri, Florence, Italy
[8] Department of Astronomy, University of Geneva, Versoix, Switzerland
[9] Pontificia Universidad Católica de Chile, Santiago, Chile
[10] Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, UK
[11] INAF, IASF-MI, Milano, Italy
[12] Faculty of Engineering and Physical Sciences, University of Southampton, UK
[13] INAF – Astrophysics and Space Science Observatory Bologna, Italy
[14] INAF – Osservatorio Astronomico di Roma, Italy
[15] Department of Physics, University of Oxford, UK
[16] Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, CAUP, Porto, Portugal
[17] Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France
[18] School of Physics Astronomy and Mathematics, University of Hertfordshire, UK
[19] EPFL, Observatoire de Sauverny, Versoix, Switzerland
[20] Institute of Theoretical Astrophysics, University of Oslo, Norway
[21] University of Bologna, Department of Physics and Astronomy (DIFA), Italy
[22] Leibniz-Institut für Astrophysik Potsdam (AIP), Germany
[23] STFC, Daresbury Laboratory, Sci-Tech Daresbury, UK
[24] Institut de Recherche en Astrophysique et Planétologie, Toulouse, France
[25] UCL Department of Space and Climate Physics, London, UK
[26] CEA, IRFU, DAp, AIM, Université Paris-Saclay, Université Paris Diderot, France
[27] INAF – Osservatorio Astronomico di Trieste, Italy
[28] Institut d'Astrophysique Spatiale, Orsay, Université Paris Sud, France
[29] School of Physics and Astronomy, University of Cardiff, UK
[30] Dept of Physics & Astronomy, University College London, UK
[31] Astrophysics Research Group, Surrey University, UK
[32] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France
[33] Observatoire Astronomique, Université de Strasbourg, France
[34] INAF – Osservatorio Astronomico di Padova, Italy
[35] INAF – Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy
[36] Department of Physics, Durham University, UK
[37] Liverpool John Moores University, UK
[38] School of Physical Sciences, The Open University, Milton Keynes, UK
[39] BlueShadows Ltda., Santiago, Chile
[40] School of Physics and Astronomy, University of St Andrews, UK
[41] Appleton Laboratory, STFC, Harwell Campus, UK
[42] Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing, China
[43] School of Physics and Astronomy, University of Birmingham, UK
[44] Armagh Observatory & Planetarium, Armagh, Northern Ireland
[45] Department of Physics, University of Lancaster, UK
[46] Department of Physics, University of Bath, UK

MOONS is the new Multi-Object Optical and Near-infrared Spectrograph currently under construction for the Very Large Telescope (VLT) at ESO. This remarkable instrument combines, for the first time, the collecting power of an 8-m telescope, 1000 fibres with individual robotic positioners, and both low- and high-resolution simultaneous spectral coverage across the 0.64–1.8 μm wavelength range. This facility will provide the astronomical community with a powerful, world-leading instrument able to serve a wide range of Galactic, extragalactic and cosmological studies. Construction is

now proceeding full steam ahead and this overview article presents some of the science goals and the technical description of the MOONS instrument. More detailed information on the MOONS surveys is provided in the other dedicated articles in this Messenger issue.

Introduction

Over the last two decades several observational milestones have dramatically changed our knowledge of the Universe. Measurements of the Cosmic Microwave Background, high-redshift supernovae and large-scale structure have revealed that 96% of the density of the Universe consists of currently unexplained Dark Energy and Dark Matter, and less than 4% is in the form of baryons. Yet most of the information we have comes from luminous, baryonic matter. Understanding the nature of the dark components which dominate the global expansion and large-scale structure of the Universe along with the physical processes that affect baryons and shape the formation and evolution of stars and galaxies is amongst the most fundamental unsolved problems in science.

Answering these important questions requires an accurate reconstruction of the assembly history of stars and galaxies over virtually all of cosmic time in order to decode the building blocks of the Universe. The Milky Way offers a unique opportunity to reconstruct the assembly history of a prototypical spiral galaxy by looking at the individual ages, chemical abundances, and orbital motions of its stellar populations. Looking far beyond our Galaxy, it is also essential to trace the evolution of galaxy properties (star formation, chemical enrichment, mass assembly, etc.) over the whole cosmic epoch if we are to investigate the effects of age and environment. Ideally, these studies should be pushed to the highest redshifts — when the Universe was just a few hundred million years old — and young galaxies are key to understanding the physics of the early Universe and cosmic re-ionisation. Addressing these fundamental science goals requires accurate determinations of stellar and galactic physical properties, as well as precise measurements of the spatial and chemical distribution of stars in the Milky Way and the 3D distribution of galaxies at different epochs.

In order to address this fundamental science, the MOONS instrument has been developed focusing on three essential parameters: sensitivity, multiplexing and wavelength coverage (the full list of key instrument parameters is given in Table 1)[1,2]. In respect of sensitivity, the VLT is currently one of the largest infrared and visible telescopes in the world in terms of collecting area, and every element of the MOONS instrument itself has been optimised for high transmission. The multiplex of 1000 is a factor of 20 larger than current spectrographs operating in the near-infrared; this is limited by the budget available, the capability to manufacture very large optics, and space on the Nasmyth platform for the large cryostat (which is already more than 4 m high — see Figure 2). Finally, the broad wavelength coverage of MOONS, from 0.645 µm to 1.8 µm, extending into the near-infrared, is critical for observing heavily dust-obscured regions of our Milky Way as well as for opening a window onto the high-redshift Universe. To meet the aspirations of both the Galactic and extragalactic scientific communities, MOONS offers both low- and high-resolution spectroscopy. In the low-resolution mode ($R \sim 4000$–7000), the entire 0.645–1.8 µm range is observed simultaneously across the *RI*, *YJ* and *H* atmospheric windows. In the high-resolution mode the *YJ* channel remains unchanged at $R \sim 4000$, while the two high-resolution dispersers are inserted in the RI and H bands: one with $R > 9000$ around the Ca triplet region

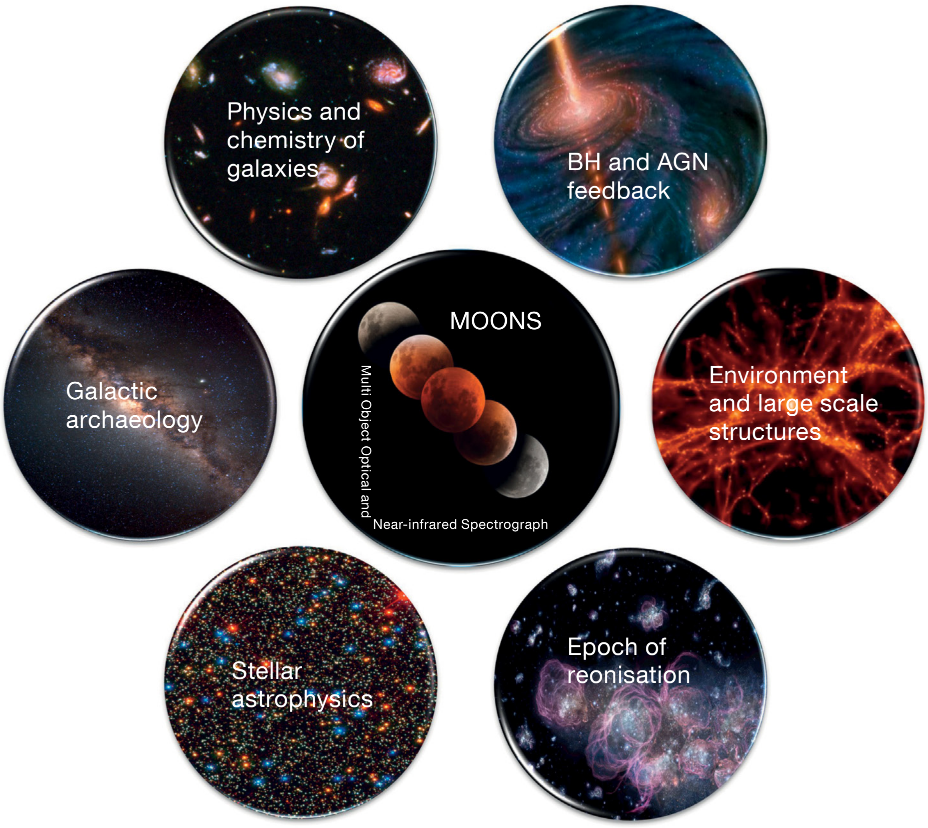


Figure 1. The key science drivers that have shaped the requirements of the MOONS instrument:
- The ability to obtain radial velocities and detailed stellar abundances for millions of stars, especially in the obscured regions of the Galaxy, to reconstruct the chemo-dynamical properties of our Milky Way.
- The capability to observe key spectral diagnostics for millions of distant galaxies up to the epoch of re-ionisation at $z > 7$, to determine the physical processes that shape their evolution and the impact of central supermassive black holes and the environments in which galaxies live, disentangling nature versus nurture effects.

to measure stellar radial velocities, and another with $R \sim 19\,000$ in the H band for detailed measurements of chemical abundances.

The science drivers and the legacy value

The wealth of science that a highly multiplexed, near-infrared spectrograph like MOONS can generate is undeniably vast and it has been a common aspiration within the ESO community for a long time. MOONS will fill a crucial gap in discovery space which could never be addressed by only optical spectroscopy or low-multiplex near-infrared spectroscopy.

Within the 300 nights of Guaranteed Time Observations (GTO) obtained in return for building the instrument, the MOONS Consortium has developed a coherent set of surveys covering a large fraction of the history of the Universe, from cosmic dawn (13 billion years ago) to the present epoch, across many astrophysical fields (see Figure 1). About 100 GTO nights are devoted to Galactic surveys (see Gonzalez et al., p. 18). The aim is to investigate the nature of the heavily obscured regions of the Galactic bulge (unachievable with optical spectrographs), as well as providing new insights into the chemo-dynamical structure of the thin and thick Galactic discs, and for targeted studies of satellites and streams in the halo.

The other ~ 200 GTO nights will focus on galaxy evolution across cosmic time (see Maiolino et al., p. 24). The goal is to provide a complete picture of the integrated properties of the stellar populations and the ionised interstellar medium (ISM) of galaxies up to high redshift in a SDSS-like survey, including a large number of Lyα emitting galaxies up to $z \sim 10$, and use this to investigate in a systematic way the role that environment and black hole feedback have on the formation and evolution of galaxies with redshift.

The combination of MOONS GTO surveys and open-time surveys will provide an invaluable legacy. Even under the conservative assumption that MOONS is used only for 100 nights a year (i.e., sharing the

Table 1. MOONS key instrument parameters.

Parameter	Value
Telescope	VLT, 8 m
Field of view	25 arcminutes in diameter
Multiplex	1001
On-sky aperture of each fibre	1.2 arcseconds
Field coverage	> 3 fibres can reach any point in the focal plane
# of fibres within a 2-arcminute diameter	7
Minimum fibre separation	10 arcseconds
Spectral channels	*RI*, *YJ* and *H* bands observed simultaneously
Resolution modes	Low and high resolution
Low-res simultaneous spectral coverage	0.64 – 1.8 μm
Low-res spectral resolution	$R_{RI} = 4100$, $R_{YJ} = 4300$, $R_H = 6600$
High-res simultaneous spectral coverage	$\lambda_{RI} = 0.76 - 0.89\ \mu m$, $\lambda_{YJ} = 0.93 - 1.35\ \mu m$, $\lambda_H = 1.52 - 1.64\ \mu m$
High-res spectral resolution	$R_{RI} = 9200$, $R_{YJ} = 4300$, $R_H = 19700$
Throughput	> 30% in low resolution, > 25% in high resolution
Sensitivity (point sources) in 1 hr integration	See Figure 3 for details
Continuum high res	S/N > 60 at $H_{AB} \sim 17$ and $RI_{AB} \sim 17.5$
Continuum low res	S/N > 5 at mag(AB) ~ 23 rebinning to $R = 1000$ after sky subtraction
Emission lines	S/N > 5 for a line flux of $> 2 \times 10^{-17}$ erg s^{-1}cm^{-2}, FWHM = 200 km s^{-1}
Calibration methods	Daytime flat fields, attached flats as part of observations, ThAr lamps for wavelengths
Observing overheads	Fibre positioning time < 2 mins Attached flats + 2 mins
Acquisition star limiting mag	V ~ 21 mag (in 30 sec exposure)

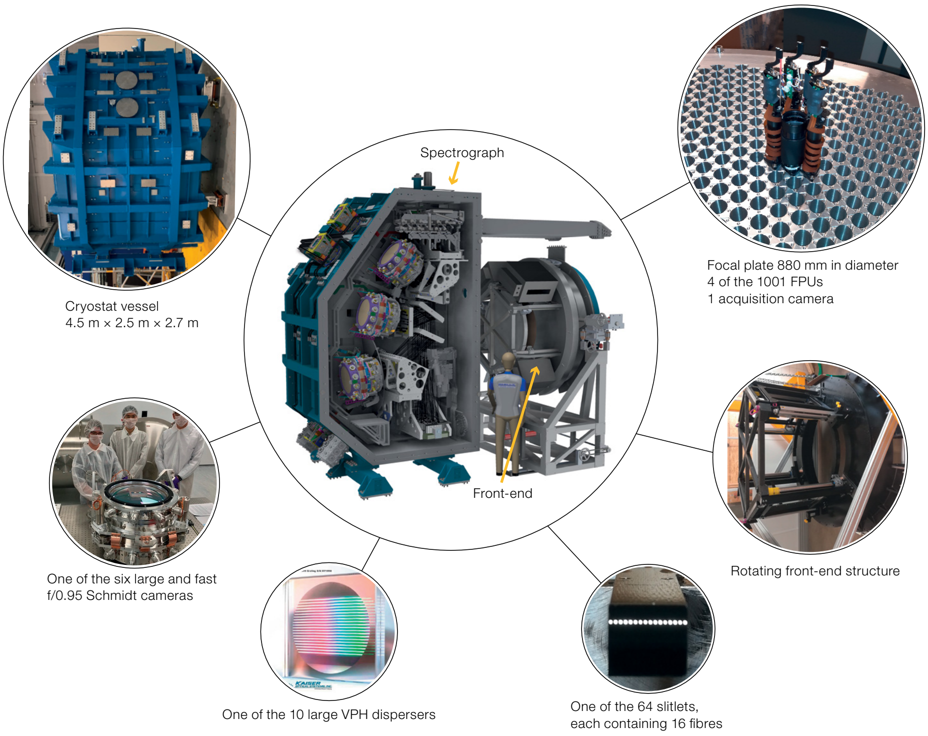


Figure 2. The central figure shows the computer-aided design (CAD) model of the MOONS instrument; the rotating front end and the spectrograph are highlighted. The other images show the real hardware being integrated. From top right and clockwise: the focal plate with four mounted fibre positioning units (FPUs) and one acquisition camera; the structure of the rotating front end that will host the plate with the FPUs, the calibration unit and the metrology system; one of the slitlets with 16 mounted fibres; one of the 10 high efficiency VPH dispersers; one of the six Schmidt cameras; and the cryostat vessel.

telescope equally with the other 2 instruments mounted on the UT), it will offer the scientific community ~ 1 000 000 fibre-hours every year. This figure will be even more if in the future one of the UTs is operated in survey mode. On a timescale of 10 years, which is the very minimum lifetime of the instrument, Legacy Surveys with MOONS will provide radial velocities and detailed chemical abundances for tens of millions of stars in our Galaxy and beyond, as well as spectra for millions of galaxies at $0 < z < 10$, providing key spectral diagnostics and environmental information. This will produce a huge and unique dataset of high-quality spectra and the essential deep spectroscopic follow-up of current and future optical and near-infrared imaging surveys or facilities (for example, Gaia, VISTA, UKIDSS, VST, Pan-STARRS, Dark Energy Survey, LSST, Euclid), as well as of objects observed at other wavelengths using, for example, ALMA, Herschel, eRosita, LOFAR, WISE, ASKAP, MeerKAT, etc. Last but not least, MOONS will offer a unique mine from which targets will be selected for detailed follow-up with ESO's Extremely Large Telescope for years to come.

The MOONS instrument

MOONS is a fibre-fed spectrograph designed to use the full 25-arcminute-diameter field of view (FoV) of one of the Unit Telescopes (UT) of the VLT. The instrument consists of the three major sub-systems shown in Figure 2: the part that is mechanically attached to the telescope and couples the light into the optical fibres (called the rotating front end); the two triple-arm spectrographs — in which the light from the fibres is dispersed and recorded; and the instrument control.

The first element in the optical path of the instrument is the field corrector made of two large lenses of almost 1 m in diameter (and ~ 110 mm thick), which provides a fully corrected field of 25 arcminutes in diameter; this is the largest field possible at the VLT.

The fibres for science observations are deployed on the focal plane created by the field corrector using 1001 miniature fibre positioning units (FPUs), allowing us to configure an entire observation in less than two minutes. Each fibre is connected to its own pick-off unit, which has a footprint of 25 mm fixed on the focal plane and is equipped with two rotating arms[3]. The combination of the two rotations (like the combined motion of elbow and shoulder) allows the fibre to patrol an area with a diameter of 50 mm (~ 1.5 arcminutes on the sky), with an accuracy of better than 20 µm (i.e., less than a third of the diameter of a human hair), which corresponds to 0.05 arcseconds on the sky. The FPUs will be able to achieve this positioning accuracy using state-of-the art stepper motors, but in order to monitor this and make any calibration adjustments there is also an external metrology system capable of precisely measuring the position of each fibre. On the focal plane, embedded within the FPUs, there are 20 acquisition and secondary guiding cameras used to acquire the science field and do a fine alignment of the instrument on the sky. The rotating front end also hosts a novel concept of calibration unit, which uses a projector (like those in cinemas) to illuminate a screen coated in a Lambertian diffuser to guarantee high quality wavelength calibration and flat fielding for all fibres. Indeed, to ensure excellent sky subtraction it is critical that the relative transmission of all the fibres is known very accurately, to better than 1%, and this highly homogeneous illumination is achieved via the calibration unit.

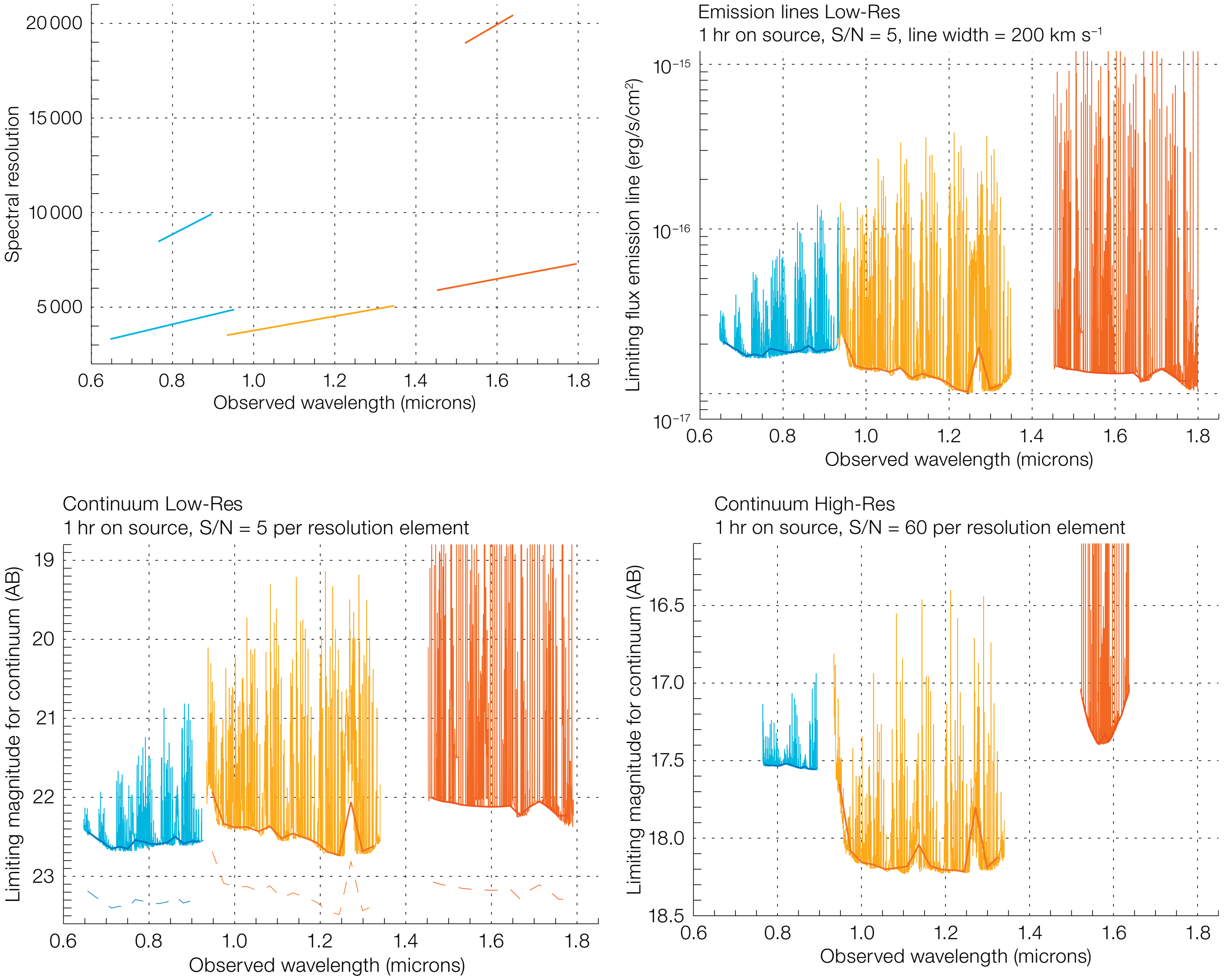
Once the light from stars and galaxies is collected at the front end it is then fed through the fibres to two identical triple-arm spectrographs enclosed in a single cryostat vessel that keeps the optical elements inside at a temperature of –130 degrees C in order to reduce the background in the near-infrared.

In each of the two spectrographs the light from 512 fibres — arranged in 32 slitlets[b], each containing 16 fibres (see Figure 2) — is split by dichroic filters into three wavelength ranges or channels (*RI*, *YJ* and *H*). Each of the two MOONS spectrographs has five highly efficient volume phase holographic (VPH) dispersers, three for the low-resolution mode and two for the high-resolution mode. The two triple-arm spectrographs are mounted back-to-back on the optical bench, which makes it possible to switch between the high- and low-resolution modes in the *RI* band (and similarly for the *H* band) using a single common linear mechanism that passes straight through the optical bench. In each channel, the light dispersed by the VPHs is refocused by using the fastest large cameras ever built for astronomy (to our knowledge). Indeed, these Schmidt-like cameras have a very fast *f*-number of *f*/0.95. Each camera is also very compact and made of just two lenses (glued one inside the other) and one mirror to bring the image into focus on a detector (see Figure 2), and is therefore easy to align. Finally, the light — which has travelled for billions of years in some cases — will be recorded on state-of-the-art detectors. The two infra-red channels (*YJ* and *H*) will exploit the new Hawaii 4RGs 15 µm-pixel detectors and the optical channel (*RI*) will use fully depleted Lawrence Berkeley National Laboratory (LBNL) red-sensitive CCDs.

Since the very beginning of the project, the focus (and the challenge to the engineering team) has been to maximise the quality and the throughput of the instrument or, in other words, the mantra has been "transmit as many photons as physically possible!". For this reason, all the components described above have been optimised in terms of design, material, coating etc. to reach the high sensitivity shown in Figure 3.

Observation preparation

For complex instruments and particularly for multi-object spectrometers, the usual ESO p2 software used to prepare the observations is complemented by the addition of instrument-specific detailed configuration software. The observation preparation software called MOONLIGHT will perform automatic allocation of fibres to science targets, including optimisation of fibre allocations and accounting for mechanical constraints of the positioners. In order to have high allocation efficiency of the fibres on targets, some overlap between neighbouring patrol fields is needed, with one fibre being able to patrol up to the centre of the neighbouring cell. However, this feature can increase the chances of collisions during positioning. To avoid such



collisions, we have developed an algorithm for the path analysis, which calculates in advance the best trajectory and motion of each motor.

Observing strategies and sky subtraction

Accurate subtraction of the sky background is critical when observing faint sources, particularly in the near-infrared, where strong OH sky lines dominate the background. To achieve this goal, we have implemented multiple methods. First of all, the spectral resolving power of $R > 4000$ for the medium-resolution mode ($R > 6500$ in the *H* band) ensures that at least 60–70% of the observed regions in the *Y*, *J* or *H* bands are completely free from OH airglow. Sky subtraction with fibres is challenging since their efficiency might change (even slightly) when they move. For this reason, particular attention has been devoted during the manufacturing of the fibres and their routing within the instrument to minimise the variation of focal ratio degradation (FRD), which has been measured to be << 1%. In order to remove any residuals, it is also possible to obtain a fast attached flat after the fibres have been reconfigured and are in their science position. To further optimise the sky subtraction, the fibre positioners have been designed to have overlapping patrol

Figure 3. Top left: Spectral resolution $R = \lambda/\Delta\lambda$ as a function of wavelength for the low-resolution and high-resolution modes. In all the panels showing sensitivity, the thick solid lines show the typical value outside strong OH sky lines. At the resolution of MOONS more than 60–70% of the observed regions are completely free from OH sky lines. Top right: limiting flux for emission lines in low-resolution mode in the three simultaneous channels, for 1 hour on-source integration with S/N = 5 at the line peak. Bottom left: limiting magnitude in continuum for low-resolution mode in the three simultaneous channels, for 1 hour on-source integration with S/N = 5 per resolution element (~ 3 pixels) and dashed lines when rebinned to a resolution R = 1000 after sky subtraction. Bottom right: limiting magnitude in continuum for high-resolution mode in the three simultaneous channels, for 1 hour on source integration with S/N = 60 per resolution element (~ 3 pixels).

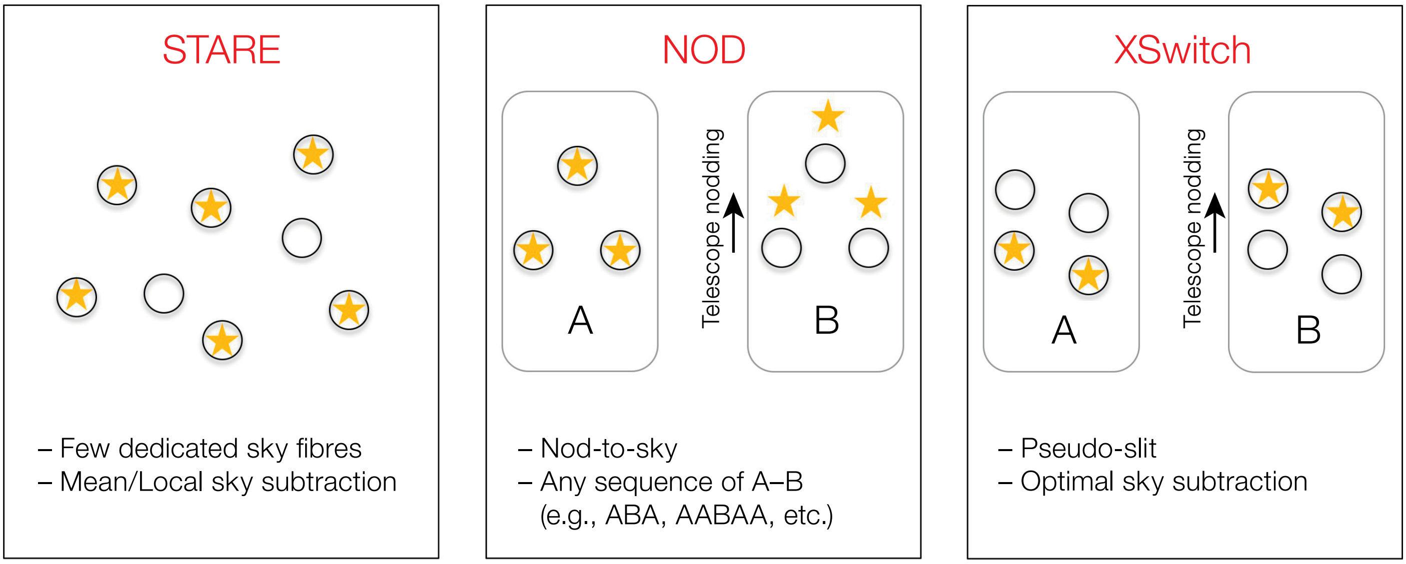


Figure 4. The three possible MOONS observing strategies envisaged for sky subtraction.

fields and are capable of being placed at a distance of 10 arcseconds from each other, so as to sample the sky very close to the science target.

These considerations are driving the three possible observing strategies envisaged for MOONS (see list below and Figure 4). During commissioning these strategies will be tested and the performance of sky subtraction evaluated in order to provide guidelines to users.

1. *Stare:* The vast majority of fibres will be on the targets, with dedicated sky fibres distributed across the focal plane. The number of sky fibres can be determined by the user.
2. *Stare+nod:* The majority of, if not all, fibres will be on the targets and the telescope is then nodded to a nearby sky position. This has the advantage that the sky flux will pass through the same fibre as the target, thus removing many instrumental effects. The quality of sky subtraction will depend on the frequency of sky nods.
3. *XSwitch:* This provides a pseudo-slit observation with the most accurate sky subtraction. Every science fibre will have an adjacent sky fibre at the same fixed distance (10 < *d* < 30 arcseconds) and same direction. The telescope is then nodded by the same distance and direction, so that object and sky fibres are reversed. This observing pattern strategy allows both temporal and spatial sky variation to be removed, as well as accounting for instrumental effects (see Rodrigues et al., 2012 for more details and on-sky testing of this strategy).

The Consortium

Reflecting the wide range of science goals, the MOONS Consortium builds on the scientific and technical expertise of a range of institutes in Chile, France, Germany, Italy, Norway, Portugal, Switzerland, the United Kingdom, and ESO. It includes ~ 100 engineers and 150 scientists across ~ 50 institutes. Table 2 shows the main roles of each of the institutes involved in the construction of the instrument.

Schedule

The MOONS project passed the Final Design Review (FDR) in 2017 and is now fully in the assembly integration and verification (AIV) phase. The vast majority of the components have been manufactured and are now being integrated in Edinburgh. The Provisional Acceptance in Europe (PAE) is foreseen for the end of 2021, followed by the installation and commissioning at the VLT at the beginning of 2022 (see Figure 5).

References

Rodrigues, M. et al. 2012, Proceedings of the SPIE, 8450E, 3HR

Links

[1] The official MOONS website: www.vltmoons.org
[2] The MOONS website at ESO: https://www.eso.org/sci/facilities/develop/instruments/MOONS.html
[3] See the fibre positioning units in action at https://vltmoons.org/resources/.

Notes

[a] For information contact Michele Cirasuolo at mciras@eso.org.
[b] A short anecdote: A very small fraction of the light coming from the fibres does not reach the detector immediately but bounces back and forth between the optical surfaces and when it reaches the detector it creates a “ghost” image! That image is adding noise and therefore degrading the science performance. When we discovered this problem, we had to think how to remove this effect. In order to do this each slitlet was equipped with a special component, tilted with respect to the optical axis, to deviate the “ghost” away from the detector. During a telecon someone said: “it works like an exorcist; the ghost has been evicted”. Since then this special component is called “the Exorcist”!

Table 2. Role of the consortium construction partners.

Institute	Work package	Logos
STFC UK Astronomy Technology Centre Edinburgh	Project office, fibre positioning units, calibration unit, cryostat, detector adjustment module, AIV, control software	
Cambridge University	Camera opto-mechanics, assembly and testing	
Eidgenössische Technische Hochschule (ETH) Zürich	Fibre positioning unit	
INAF – Firenze	Optical design, exchange VPH mechanisms	
INAF – Roma	Acquisition cameras end-to-end modelling	
INAF – Milano	Observation preparation software and path analysis	
GEPI – Paris	Fibre assembly, slit and shutters, data reduction software	
University of Geneva	Instrument control electronics	
Instituto de Astrofísica e Ciências do Espaço	Field corrector, rotating front end structure, cable wrap	
Pontificia Universidad Católica de Chile	Metrology system, instrument control software	
ESO	Detector arrays and CCDs	

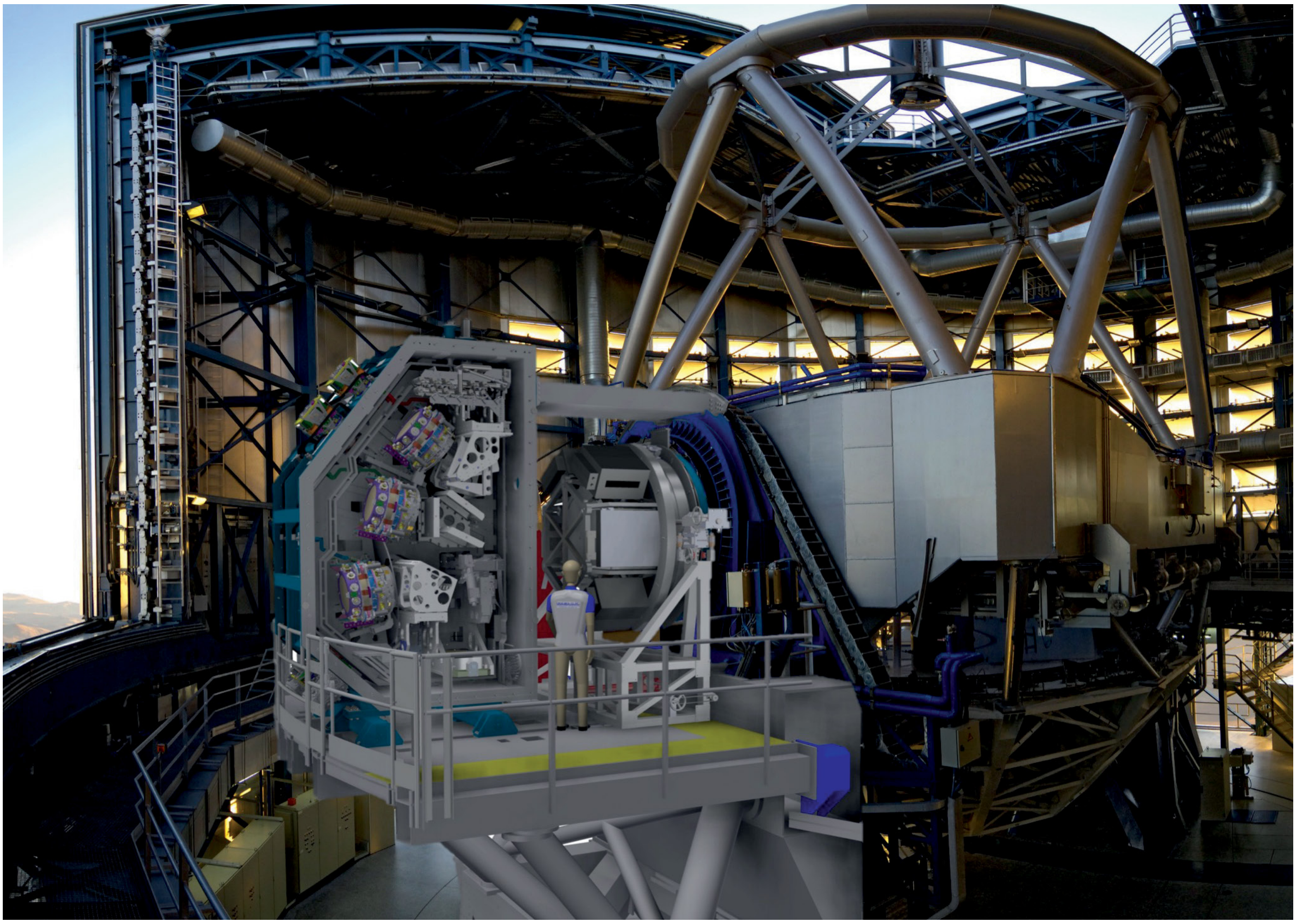


Figure 5. Artist's impression of MOONS on the Nasmyth platform at the VLT.

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MOONS Surveys of the Milky Way and its Satellites

Oscar A. Gonzalez[1]
Alessio Mucciarelli[2,3]
Livia Origlia[3]
Mathias Schultheis[4]
Elisabetta Caffau[5]
Paola Di Matteo[5]
Sofia Randich[6]
Alejandra Recio-Blanco[4]
Manuela Zoccali[7,8]
Piercarlo Bonifacio[5]
Emanuele Dalessandro[3]
Ricardo P. Schiavon[9]
Elena Pancino[6]
William Taylor[1]
Elena Valenti[10]
Álvaro Rojas-Arriagada[7,8]
Germano Sacco[6]
Katia Biazzo[11]
Michele Bellazzini[3]
Maria-Rosa L. Cioni[12]
Gisella Clementini[3]
Rodrigo Contreras Ramos[7,8]
Patrick de Laverny[4]
Chris Evans[1]
Misha Haywood[5]
Vanessa Hill[4]
Rodrigo Ibata[13]
Sara Lucatello[14]
Laura Magrini[6]
Nicolas Martin[13]
Brunella Nisini[11]
Nicoletta Sanna[6]
Michele Cirasuolo[10]
Roberto Maiolino[15]
José Afonso[16,17]
Simon Lilly[18]
Hector Flores[5]
Ernesto Oliva[6]
Stéphane Paltani[19]
Leonardo Vanzi[7]

[1] UK Astronomy Technology Centre, Edinburgh, UK
[2] Università di Bologna, Italy
[3] INAF – Astrophysics and Space Science Observatory Bologna, Italy
[4] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France
[5] GEPI, Observatoire de Paris, Université PSL, CNRS, France
[6] INAF – Osservatorio Astrofisico di Arcetri, Italy
[7] Pontificia Universidad Católica de Chile, Chile
[8] Millennium Institute of Astrophysics, Chile
[9] Liverpool John Moores University, UK
[10] ESO
[11] INAF – Osservatorio Astronomico di Roma, Italy
[12] Leibniz-Institut für Astrophysik Potsdam (AIP), Germany
[13] Observatoire Astronomique, Université de Strasbourg, France
[14] INAF – Osservatorio Astronomico di Padova, Italy
[15] Department of Physics, Cavendish Laboratory, Cambridge, UK
[16] Instituto de Astrofísica e Ciências do Espaço, Universidade de Lisboa, Portugal
[17] Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Portugal
[18] ETH Zurich, Switzerland
[19] University of Geneva, Switzerland

The study of resolved stellar populations in the Milky Way and other Local Group galaxies can provide us with a fossil record of their chemo-dynamical and star-formation histories over timescales of many billions of years. In the galactic components and stellar systems of the Milky Way and its satellites, individual stars can be resolved. Therefore, they represent a unique laboratory in which to investigate the details of the processes behind the formation and evolution of the disc and dwarf/irregular galaxies. MOONS at the VLT represents a unique combination of an efficient infrared multi-object spectrograph and a large-aperture 8-m-class telescope which will sample the cool stellar populations of the dense central regions of the Milky Way and its satellites, delivering accurate radial velocities, metallicities, and other chemical abundances for several millions of stars over its lifetime (see Cirasuolo et al., p. 10). MOONS will observe up to 1000 targets across a 25-arcminute field of view in the optical and near-infrared (0.6–1.8 μm) simultaneously. A high-resolution ($R \sim 19\,700$) setting in the *H* band has been designed for the accurate determination of stellar abundances such as alpha, light, iron-peak and neutron-capture elements.

Scientific motivation

The need to obtain a large-scale empirical description of the Milky Way and its satellites has defined ambitious requirements for the development of cutting-edge astronomical technology during the last decade. Large international collaborations have been assembled to use this new instrumentation to produce a chemo-dynamical map of their resolved stellar populations in exquisite detail. However, there are several questions that unfortunately cannot be fully addressed with the available instrumentation.

The central regions of the Milky Way, specifically those near the Galactic plane, are currently inaccessible to high spectral resolution observations with sufficiently large number statistics and spatial coverage because of an inability to efficiently overcome the effect of the immense amounts of interstellar dust across the disc. As a consequence, we are currently unable to reconstruct the entire history of the Milky Way down to its most central components, thus missing one of the critical pieces in the puzzle of galaxy formation. The only way to remedy this is to carry out a coherent, large-scale mapping of the stellar populations of the Milky Way, particularly focused on the in-plane regions of the bulge and the inner disc, providing the key missing ingredient necessary to fully understand the processes behind the formation and evolution of barred disc galaxies.

Similarly, the globular cluster system of the Milky Way has long been used to learn about the evolution of the Galaxy. The study of the stellar populations of globular clusters in the inner Milky Way can give us important clues about the early stages of the Galaxy's formation by tracing the most vigorous epochs of *in situ* star formation as well as its early accretion history. However, the study of inner, highly reddened Milky Way clusters is hampered by the small sample of stars with suitable infrared spectroscopy and the lack of homogeneity with respect to field stars. Constructing a large homogeneous sample of stars from inner globular clusters and the surrounding fields with high-quality measurements of kinematics and chemistry — which can be homogeneously compared to those of the bulge — is critical to understanding the origin of the clusters and their contribution to the relatively metal-poor component of the Milky Way bulge.

On the other hand, the study of the formation and evolution of young star clusters and their stellar populations represents the backbone of research in modern astrophysics, as it has a strong impact on our understanding of key open issues, from the processes of star and planet formation to the assembly and evolution of the Milky Way and galaxies in general. However, a homogeneous determination of precise radial velocities and chemical content of the optically faint cluster populations (intrinsically redder objects, embedded stars, embedded/reddened clusters currently not accessible because of their large extinctions and densities) is vital to achieving full sampling of the parameter space (for example, lower masses, presence of gas, position in the Milky Way disc).

Furthermore, beyond the Milky Way, the proximity of the galaxies in the Local Group allows us to observe their individual stars both with spectroscopy and photometry, as well as to study in detail the characteristics of their stellar populations. In particular, the closest satellites of the Milky Way are the Large Magellanic Cloud (LMC), the Small Magellanic Cloud (SMC), and the remnant of the Sagittarius dwarf spheroidal galaxy. These three galaxies are excellent targets with which to investigate and unravel the star formation history of irregular/dwarf galaxies that have experienced gravitational interactions between each other and/or with the Milky Way. Thus, chemical and kinematical information about the stellar populations in the Magellanic Clouds and the Sagittarius dwarf spheroidal galaxy is a fundamental complement to the corresponding information for the Milky Way.

The MOONS surveys will be focused on the detailed kinematic and chemical characterisation of the resolved stellar populations in the Milky Way and its closest satellites, with a focus on environments that continue to be poorly sampled by previous and ongoing spectroscopic surveys. We will dedicate two main surveys to this objective:

- Reddened Milky Way Survey (70 nights), which will sample the chemo-dynamics of the stellar populations in the Galaxy's inner 3 kpc and in a few other disc regions affected by severe extinction in the visual;
- Milky Way Satellites Survey (30 nights), which will sample the stellar populations in the central disc/bar region of the Magellanic Clouds and in the Sagittarius galaxy and streams.

Both surveys will obtain high-signal-to-noise spectra (*SNR* ~ 50–100) to obtain temperatures and surface gravities (from photometric and spectroscopic diagnostics), abundances of iron, α-elements (from optical and near-infrared spectra), CNO and possibly a few other light elements (from near-infrared spectra only), and radial velocities.

The reddened Milky Way survey

The MOONS REDdened Milky WAY (REDWAY) survey will sample 0.5 million stars across the Galactic plane (Figure 1) tracing red-clump stars in the bulge/bar and inner disc regions, red-giant stars of the inner globular cluster system and the nuclear bulge, as well as mapping young embedded star clusters. It will take full advantage of three aspects of MOONS: i) its high-density targeting capabilities to obtain up to 900 stars in each 25-arcminute diameter pointing and the remaining ~ 100 fibres on sky regions[a], ii) its high-resolution mode — in *RI* (*R* ~ 9200), *YJ* (*R* ~ 4300), and *H* (*R* ~ 19 700) — to disentangle key spectral features, and iii) the 8-m aperture of the VLT and high efficiency of MOONS to produce exquisite, high-signal-to-noise spectra in the near-infrared.

The nuclear region

A key ingredient for understanding the processes taking place in the central regions of galaxies is to perform resolved stellar population studies in our own Galaxy. MOONS will provide the opportunity to obtain high-resolution spectra for stars in the nuclear star cluster and disc, thus allowing the measurement of radial velocities, [Fe/H], CNO, alpha, and a few other elements.

The survey will cover the nuclear bulge with 15 fields (blue circles in Figure 1) covering $-1 < l < 1$ degrees and $-0.5 < b < 0.5$ degrees corresponding to a scale height coverage of ~ 50 pc and scale length of ~ 140 pc. A total of ~ 13 000 red giant stars will be observed. In the central field, at *l*,*b* = 0,0 degrees, a subset of 200 stars will sample the innermost 10 pc region, therefore mapping the nuclear star cluster.

The resolved stellar populations and kinematics of these extreme systems, as seen in the Milky Way by MOONS, will become a unique benchmark template for unresolved nuclear clusters in external galaxies as well as providing vital input regarding their formation scenarios and establishing their link to their larger-scale host components.

The bulge/bar at low latitudes

In order to understand the complex structure (and the formation mechanism) of components potentially co-existing in the in-plane regions of the Galaxy (for example, Wegg, Gerhard & Portail, 2015), it is important to obtain a large sample of stars mapped across all of the midplane to characterise and identify the orbits and chemical abundances of stars. In order to satisfy this objective, a suitable grid of fields (shown in Figure 1 in orange) has been designed to provide the best coverage and number statistics to trace the properties of the different Galactic components to an unprecedented level of detail. The highest priority in terms of time investment has been given to the mid-plane region of the bulge where the field coverage is nearly contiguous. This is a unique property of this survey, which is not possible with any other facility because these high-density stellar fields are heavily reddened.

The survey will obtain ~ 900 red-clump stars across each of the 380 fields (at a SNR > 60 in *H* band) in these poorly explored regions, allowing us to derive statistically significant distributions of metallicities, alpha-element abundances (and potentially ages), as well as 3D velocities by combining proper motions from the VISTA Variables in the Via Lactea (VVV) survey with MOONS radial velocities to distinguish between different families of orbits and possible independ-

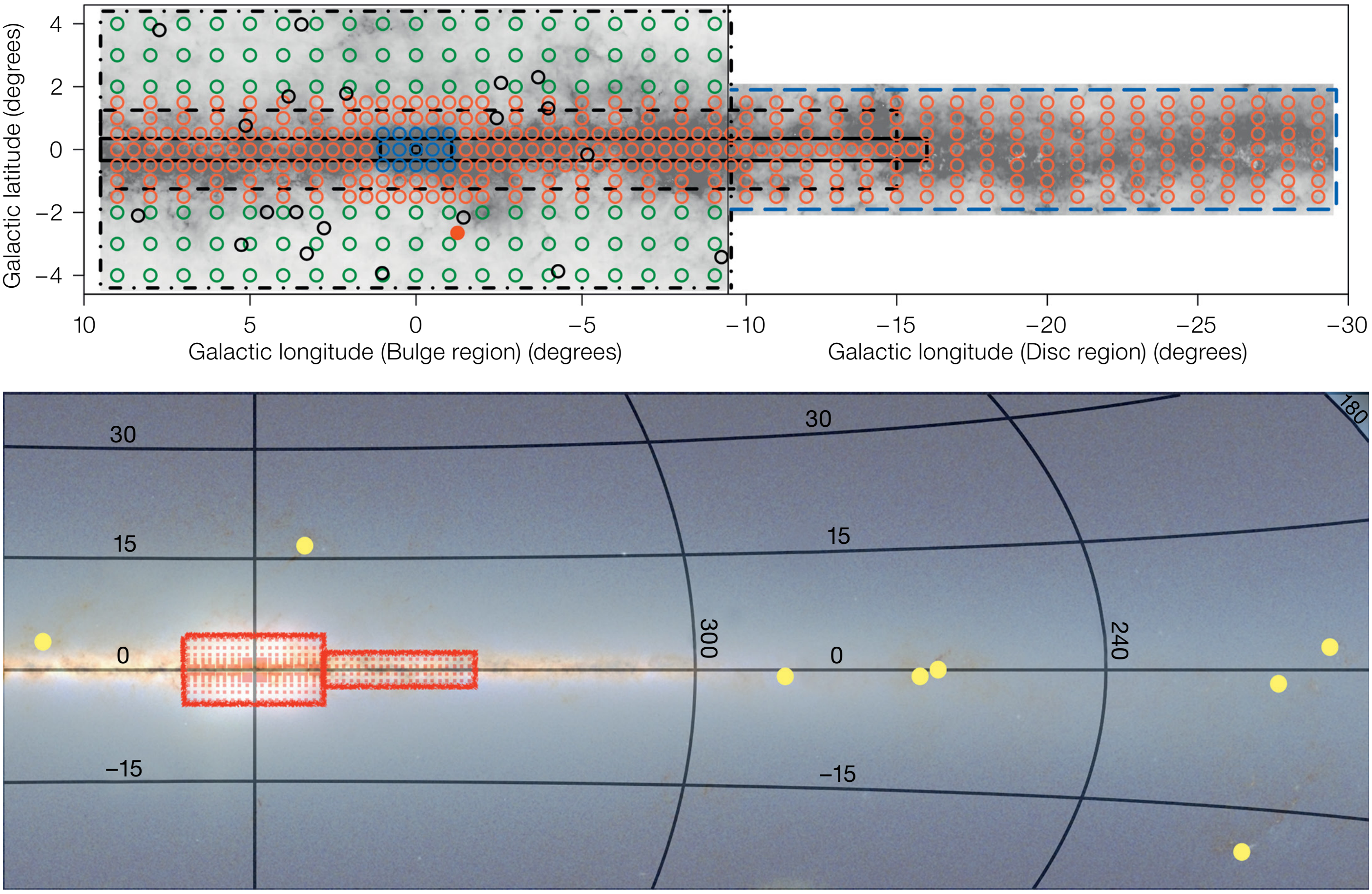

Figure 1. The top panel shows the layout of fields for the REDWAY survey. Lines mark the areas mapping the in-plane bar and inner disc (orange), boxy bulge (green), nuclear bulge (blue), bulge deep field (red), and inner galaxy clusters (black). The lower panel shows a zoomed-out view of the survey footprint showing in yellow circles the location of young clusters and star-forming regions to be mapped.

ent components that can be compared with state-of-the-art simulations.

The boxy/peanut bulge

The bulge region at $2 < |b| < 4$ degrees is the most favourable field in which to characterise the stellar population of the main bulge/bar itself without contamination from other nuclear components where other processes such as star formation might be at work, and with sufficient statistics to fully characterise the detailed chemical content and kinematics.

Recent optical surveys such as the Abundances and Radial velocity Galactic Origins Survey (ARGOS), the GIRAFFE Inner Bulge Survey (GIBS), and the Gaia–ESO Survey have unambiguously demonstrated that the bulge hosts at least two main components — a metal-poor one centred at [Fe/H] = −0.4 and a metal-rich one centred at [Fe/H] = +0.3. The two main bulge components have different kinematics and different spatial distributions. Recently, a study using the APOGEE data by Rojas-Arriagada et al. (2019) has shown that the magnesium-to-iron abundance of bulge stars is also bimodal, the separation coinciding with the separation in [Fe/H] abundance between the metal-poor and metal-rich populations. Therefore, a proper chemical separation of the two components will enable a cleaner characterisation of the kinematical and spatial properties of each of them.

The main issues that are currently unresolved are: (i) how the metal-poor component formed; and (ii) whether the large population of RR Lyrae stars in the bulge, tracing the component older than 10 Gyr, is associated with the metal-poor population or traces a third component. The high multiplexity of MOONS will allow us to perform a detailed analysis of the different populations for each line of sight, without the need to group stars to increase number statistics, therefore conserving the spatial resolution of the survey footprint. The MOONS REDWAY survey will produce a total sample of more than 102 000 stars distributed across the ~ 120 fields shown in Figure 1 in green at a SNR ~ 100 in the *H* band at $R \sim 19700$.

Bulge Deep Field

Despite the huge observational effort invested over the last decade in unveiling the star formation history of the Milky Way bulge, the missing key ingredient remains the accurate age of its stellar population. The scenario of an old (> 10 Gyr) bulge suggested by several photometric studies has been challenged by spectroscopic studies of main sequence turnoff stars that point towards the presence of a significant fraction of metal-rich stars as young as ~ 2–5 Gyr (Bensby et al., 2017). Furthermore, Haywood et al. (2016) have presented a study showing that the colour spread at the turnoff should be broader than observed, when accounting for the metallicity distribution of the bulge. They provide evidence suggesting that the correlation between age and metallicity can mimic the colour-magnitude diagram of a purely old population and showing that young stars are indeed necessary to reproduce the bulge colour-magnitude diagram. This discrepancy, and the possible explanation provided by Haywood et al. (2016), can only be settled by measuring individual ages for dwarf stars with stellar parameters and element abundances via high-resolution spectroscopy.

MOONS can observe several hundreds of main sequence turnoff stars in the Hubble Space Telescope bulge field known as the SWEEPS field (l, b) = (1.25, −2.65), which has a baseline of proper motions covering over a decade under the WFC3 Galactic Bulge Treasury programme (Brown et al., 2009). This field (shown in Figure 1 as a red circle) will be used to anchor new astrometric catalogues covering the MOONS FOV (such as DECam, Gaia DR4, LSST, and dedicated programmes) to perform a proper-motion decontamination of the bulge turnoff sequence for target selection. The MOONS main sequence turnoff stars sample will reach a SNR > 50 in the H band at R ~ 19 700, thus providing radial velocities, stellar parameters and detailed abundances. A similar strategy will be applied to Baade's Window, which requires a shorter exposure time and suffers from fewer crowding problems. These two fields will generate the largest spectroscopic sample of turnoff bulge stars (at high spectral resolution), increasing the currently available sample by a factor of 10. This will allow for a robust measurement of the age distribution of the bulge and the investigation of vertical variations as well as enabling a comparison/validation of the photometric techniques applied to both fields. It will also allow for the first time the age-metallicity-orbital behaviour of a galactic bulge to be investigated on a star-by-star basis.

Inner Milky Way Globular Clusters

MOONS offers a unique opportunity to build a homogeneous dataset of stellar abundances in each cluster, overcoming the limitation of low number statistics of previous studies, and comparing the properties of the globular cluster system with those of the field populations. The innermost Galactic regions probed by MOONS contain about one third of the whole Galactic globular cluster population. By observing tens of stars in most of these clusters, MOONS can provide the largest sample of detailed abundances of Galactic globular clusters, which will prove fundamental for all studies of Galactic stellar populations, and also for the study of globular cluster formation and early evolution (i.e., multiple populations).

The clusters to be targeted will be those for which spectroscopic observations are difficult owing to strong dust obscuration and a high density of targets (thus requiring high multiplexity over an arcminute-scale region). A total of 20 clusters will be sampled with dedicated pointings as shown in Figure 1 (black circles). In addition, fibres allocated to targets in newly discovered star clusters (for example from the VVV survey) will be included as part of the regular field survey footprint. Radial velocities, stellar parameters and abundances will be obtained for as many cluster members as possible. The number of targets will depend on the density and projected size of each cluster. However, MOONS is able to allocate tens of targets even in a very small cluster (such as NGC 6522). This is not currently possible with any other instrument in the near-infrared. High-signal-to-noise (SNR > 60 in the H band) spectra will be obtained for all observed stars to derive accurate abundances down to a magnitude of H_{AB} = 17.3, spanning the red giant branch of even the most reddened clusters (at least 4 magnitudes below the tip of the red giant branch).

Young Star Clusters

Large surveys like Gaia–ESO have yielded new results on the kinematic and dynamical properties of visible stars in (very) young clusters, such as complex kinematic structures and the puzzling discrepancy between the velocity dispersion of already formed stars and that of pre-stellar cores. Along with Gaia data, these results are revolutionising our understanding of cluster formation and early dynamical evolution.

The MOONS survey will complement surveys carried out at visible wavelengths by extensively mapping very young clusters and star-forming regions (Figure 1, bottom panel) that are partially or fully embedded and thus not accessible to previous studies, extending the critical range of masses, densities, and metallicities. The immediate goal is the determination of a) precise radial velocities of unbiased, statistically significant samples of cluster candidates, in order to derive the kinematics and dynamical status of the embedded and very low mass cluster populations; b) stellar parameters and accretion properties to fully characterise them; and c) metallicity and elemental abundances (sampling all nucleosynthetic channels) of the bright cluster members.

The survey will focus on regions where enough targets are available to exploit MOONS capabilities. It will prioritise observations in high-resolution mode down to H_{AB} ~ 18.5 and it will include faint and bright configurations in the same pointing. Bright stars will reach sufficiently high SNR (> 50) to derive elemental abundances, while for the fainter candidates only stellar parameters and radial velocities will be derived (SNR > 15–20). For both bright and faint candidate targets we will be able to derive accretion properties (the SNR will be higher in the emission lines).

The Milky Way Satellites

The LMC and SMC are the largest and most massive satellites of the Milky Way. They are classified as irregular galaxies characterised by extended, still-ongoing star formation activity, as witnessed by the wide range of ages and metallicities of their stellar populations. On the other hand, the Sagittarius dwarf spheroidal galaxy is the most spectacular case of a Galactic satellite that is being disrupted by the Milky Way tidal field (Ibata et al.,1994), as witnessed by a two-arm tidal stream that has been traced across the

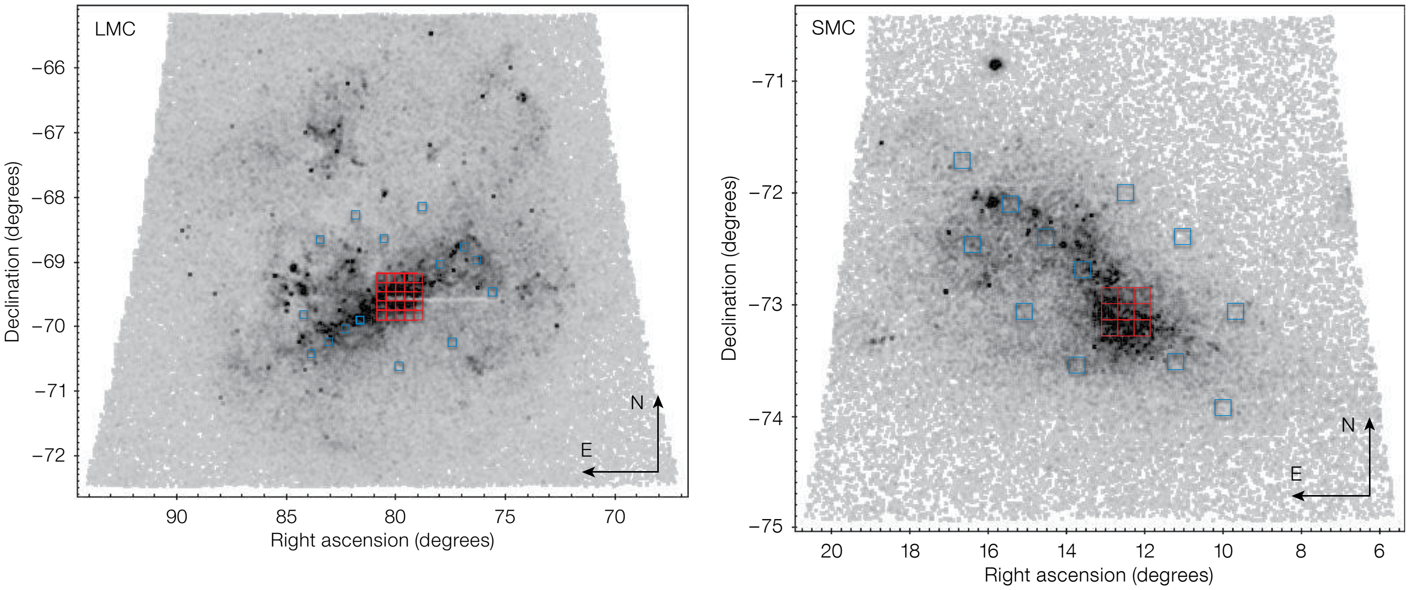

Figure 2. Map of the giant stars in the LMC (left) and the SMC (right). Red squares mark the first priority MOONS fields and blue squares show the second priority fields.

entire sky (Majewski et al., 2003). The disruption of the Sagittarius dwarf spheroidal galaxy is contributing to the buildup of the Galactic halo in terms of dark matter, stars, and globular clusters.

The multiplexing power of MOONS, coupled with its simultaneous wide spectral coverage and medium-high spectral resolution in the *I* and *H* bands, will allow us to dramatically increase the number of observed stars in the Magellanic Clouds and the Sagittarius dwarf spheroidal galaxy for which we have high quality spectra, thus providing an excellent characterisation of their stellar populations in terms of their chemistry and kinematics. A total of 116 fields covering both systems is planned to provide temperatures and surface gravities (from photometric and spectroscopic diagnostics), abundances of iron, α-elements (from optical and near-infrared spectra), CNO and possibly of a few other light elements (from near-infrared spectra only) and radial velocities.

Magellanic Clouds

The majority of studies providing information about the metallicity distribution in the Magellanic Clouds result from calcium triplet surveys (Carrera et al., 2011; Dobbie et al., 2014) of a few thousand stars. Our present knowledge of the chemical properties of the LMC is derived from optical observations collected with the ESO Fibre Large Array Multi Element Spectrograph (FLAMES) for evolved cool stars in the bright portion of the red giant branch ($V \sim 17$–17.5). Perhaps surprisingly, for a long time chemical information for SMC stars was limited to a few supergiant stars, located in some very young stellar clusters, while investigations of the stellar populations older than ~ 2 Gyr were lacking. Only very recently have Nidever et al. (2019) presented some chemical abundances of iron and α-elements from APOGEE spectra for luminous giant stars in the SMC.

However, the number of individual stars for which chemical abundances derived from high-resolution spectroscopy are available is insufficient to fully characterise the chemical enrichment history of the stellar populations of the Magellanic Clouds and to unveil possible gradients or differences in chemical enrichment in different regions of the galaxies. Similarly, existing observations of the kinematics of stars across the Magellanic Clouds are severely limited by the type of stellar populations, their spatial distribution, spectral resolution, and low number statistics. In particular, the central regions are poorly sampled, preventing us from being able to draw quantitative conclusions about the location of the gravitational centres.

The MOONS survey will produce a mosaic of 5 × 5 fields around the LMC centre (see Figure 2) to study the chemical composition and kinematics of the central bar and accurately identify the position of the LMC centre. It will also include about 17 fields located along the major axis of the bar and in the LMC disc (to investigate the chemical and kinematical properties in different LMC sub-structures) and four fields around the LMC centre, targeting the fainter, less evolved stellar population.

In the SMC, the survey will cover a mosaic of 3 × 3 fields around the SMC centre (see Figure 2) to study the chemical composition and kinematics of the densest region and accurately identify the position of the SMC centre, as well as about 13 fields along the SMC northeast extension to investigate the chemical and kinematical properties in regions associated with different sub-structures.

Additionally, a few tens of young/intermediate age stellar clusters and young clusters in binary systems will be also be observed in both galaxies. Studies of these systems can provide crucial information about the possible interactions suffered by the Magellanic Clouds in the past as well as on the mechanisms of cluster formation and evolution and their dependence on redshift and environment. Chemical abundance distributions and radial velocities will be derived for ~ 10–20 stars mapped in each cluster.

The combination of the derived abundances for stars (~ 35 000 stars in the LMC and ~ 18 000 in the SMC) down to $I_{AB} = 18$ mag ($H_{AB} < 17.6$ mag) from the MOONS survey with the star formation histories obtained from the VMC CMDs (Cioni et al., 2011), proper motions obtained from the VMC multi-epochs, and from Gaia (Gaia collaboration, Helmi et al., 2018), will provide a new picture of the structure of the Magellanic Clouds and the evolution of their stellar populations.

Sagittarius dwarf spheroidal

Several investigations of the chemical composition of the Sagittarius dwarf spheroidal galaxy are available in the literature but our knowledge of its chemistry is far from being complete or exhaustive. The metallicity distribution of the Sagittarius dwarf spheroidal galaxy is bimodal, with two main peaks at [Fe/H] = −0.5 and −1.5 dex, with an extended metal-poor tail (see for example, Bellazzini et al., 2008; Mucciarelli et al., 2017). However, the chemical composition and the distribution of the metal-poor population are poorly known as most of the available studies focus on the central region of the galaxy where the nuclear cluster M54 dominates over the Sagittarius field population in this metallicity regime (Bellazzini et al., 2008). For this reason, even if the Sagittarius dwarf spheroidal galaxy metallicity distribution is clearly dominated by its metal-rich, intermediate-age component, a complete and unbiased metallicity distribution is still lacking.

Several aspects of the chemical composition of the Sagittarius dwarf spheroidal galaxy remain unclear and large samples of medium-high resolution spectra are needed to solve some major open questions, namely: (i) its metallicity distribution, in particular the fraction of metal-poor stars (with [Fe/H] < −1 dex); (ii) the [α/Fe] abundance ratios that are ideal diagnostics for studying the contribution of Type II and Type Ia supernovae to the chemical enrichment of the system. The metal-rich component in the innermost part of the Sagittarius dwarf spheroidal galaxy shows sub-solar [α/Fe] and a knee located at [Fe/H] ~ −1.3 dex (de Boer, Belokurov, Koposov, 2015); and (iii) possible metallicity and radial velocity gradients along the main body of the galaxy. In particular, we stress that a milestone in the study of the chemical composition of the Sagittarius dwarf spheroidal galaxy will be to obtain an unbiased sample of stars in the galaxy, removing the contribution of M54.

The survey will cover a mosaic of 24 fields located within the inner 100 arcminutes of the central region of the Sagittarius dwarf spheroidal galaxy, outside the tidal radius of M54, to derive an unbiased metallicity distribution. It will also include about 16 fields outside of the core radius of the galaxy and along its major axis to investigate possible metallicity and kinematical gradients. The survey will map more than 15 000 stars down to the He clump, including about 5000 stars brighter than $I_{AB} < 18$ mag, for the Sagittarius dwarf spheroidal galaxy centre (to obtain a robust metallicity distribution). In addition, two fields will be selected along the minor axis of the Sagittarius dwarf spheroidal galaxy to investigate possible metallicity and kinematical gradients. In the less dense, most external Sagittarius dwarf spheroidal galaxy regions, the survey will make efficient use of the MOONS fibres by observing additional Milky Way stars present along the line of sight. These observations will allow us to build up a database of MOONS spectra for several thousands of thick disc stars.

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Notes

[a] This is a conservative estimate of the number of fibres allocated to sky and is expected decrease once our sky subtraction techniques are optimised using on-sky data. Therefore, the total number of targets collected by the end of the survey is likely to be larger than given in this article.

ESO/P. Horálek

Early morning at Paranal Observatory. This image shows both the VLT and the Residencia, where staff and visiting astronomers and engineers stay during their visits to Paranal Observatory.

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MOONRISE: The Main MOONS GTO Extragalactic Survey

Roberto Maiolino[1, 2, 3]
Michele Cirasuolo[4]
José Afonso[5, 6]
Franz E. Bauer[7, 8, 9]
Rebecca Bowler[10]
Olga Cucciati[11]
Emanuele Daddi[12]
Gabriella De Lucia[13]
Chris Evans[14]
Hector Flores[15]
Adriana Gargiulo[16]
Bianca Garilli[16]
Pascale Jablonka[15, 17]
Matt Jarvis[10]
Jean-Paul Kneib[17]
Simon Lilly[18]
Tobias Looser[18]
Manuela Magliocchetti[19]
Zhongyi Man[20]
Filippo Mannucci[21]
Sophie Maurogordato[22]
Ross J. McLure[23]
Peder Norberg[24]
Pascal Oesch[25, 26]
Ernesto Oliva[21]
Stéphane Paltani[25]
Ciro Pappalardo[5, 6]
Yingjie Peng[20]
Laura Pentericci[27]
Lucia Pozzetti[11]
Alvio Renzini[28]
Myriam Rodrigues[10, 15]
Frédéric Royer[15]
Steve Serjeant[29]
Leonardo Vanzi[7]
Vivienne Wild[30]
Gianni Zamorani[11]

[1] Kavli Institute for Cosmology, University of Cambridge, UK
[2] Cavendish Laboratory, University of Cambridge, UK
[3] Department of Physics and Astronomy, University College London, UK
[4] ESO
[5] Instituto de Astrofísica e Ciências do Espaço, Universidade de Lisboa, Portugal
[6] Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Portugal
[7] Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Santiago, Chile,
[8] Millennium Institute of Astrophysics (MAS), Santiago, Chile
[9] Space Science Institute, Boulder, USA
[10] Department of Physics, University of Oxford, UK
[11] INAF – Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Italy
[12] CEA, IRFU, DAp, AIM, Université Paris-Saclay, Université Paris Diderot, France
[13] INAF – Osservatorio Astronomico di Trieste, Italy
[14] UK Astronomy Technology Centre, Edinburgh, UK
[15] GEPI, Observatoire de Paris, PSL University, CNRS, Meudon, France
[16] INAF, IASF-MI, Milano, Italy
[17] Physics Institute, Laboratoire d'Astrophysique, EPFL, Switzerland
[18] Department of Physics, ETH Zurich, Switzerland
[19] INAF – IAPS, Roma, Italy
[20] Kavli Institute for Astronomy and Astrophysics, Peking University, China
[21] INAF – Osservatorio Astrofisico di Arcetri, Firenze, Italy
[22] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Nice Cedex 4, France
[23] Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, UK
[24] Department of Physics, Durham University, UK
[25] Department of Astronomy, University of Geneva, Versoix, Switzerland
[26] Cosmic Dawn Center (DAWN), Copenhagen, Denmark
[27] INAF – Osservatorio Astronomico di Roma, Monte Porzio Catone, Italy
[28] INAF – Osservatorio Astronomico di Padova, Italy
[29] School of Physical Sciences, The Open University, Milton Keynes, UK
[30] School of Physics and Astronomy, University of St Andrews, UK

The MOONS instrument possesses an exceptional combination of large multiplexing, high sensitivity, broad simultaneous spectral coverage (from optical to near-infrared bands), large patrol area and high fibre density. These properties provide the unprecedented potential of enabling, for the very first time, SDSS-like surveys around Cosmic Noon ($z \sim 1$–2.5), when the star formation rate in the Universe peaked. The high-quality spectra delivered by MOONS will sample the same nebular and stellar diagnostics observed in extensive surveys of local galaxies, providing an accurate and consistent description of the evolution of various physical properties of galaxies, and hence a solid test of different scenarios of galaxy formation and transformation. Most importantly, by spectroscopically identifying hundreds of thousands of galaxies at high redshift, the MOONS surveys will be capable of determining the environments in which primeval galaxies lived and will reveal how such environments affected galaxy evolution. In this article, we specifically focus on the main Guaranteed Time Observation (GTO) MOONS extragalactic survey, MOONRISE, by providing an overview of its scientific goals and observing strategy.

An unprecedented discovery space with MOONS

The unique observing capabilities of MOONS (see for example, Figure 1 and Cirasuolo et al., p. 10) make it the optimal match to the Sloan Digital Sky Survey (SDSS) at high redshift and specifically around the Cosmic Noon, i.e., the peak of cosmic star formation, at $z \sim 1$–2.5. Indeed, prominent optical nebular lines, typical of star-forming galaxies and active galactic nuclei (AGN), such as Hα and [OIII] 5007 Å are detectable with MOONS out to $z = 1.74$ and 2.6, respectively, while other bluer optical nebular diagnostics such as [OII] 3727 Å are already in the MOONS band at $z = 0.7$ and observable up to $z = 3.8$ (Figure 2). Key optical stellar features used to characterise the stellar populations are also in the MOONS band over this broad redshift range and will also enable the identification of passive galaxies at $z \sim 1$–2 (Figure 2).

These are all nebular and stellar diagnostics that have been successfully used to characterise hundreds of thousands of galaxies in the local universe by extensive optical spectroscopic surveys such as SDSS and Galaxy And Mass Assembly (GAMA). Accessing these spectral features will also enable MOONS to spectroscopically measure the redshifts of galaxies in the so-called redshift desert ($z \sim 1.5$), right at the peak of the cosmic star formation rate density, where the sparseness of spectral features has generally hampered the capability of optical spectrometers to identify galaxies. Of course, the broad spectral coverage of MOONS will also allow the investigation of large samples of very distant galaxies, around the epoch of reionisation, especially by observing Lyα and other transitions in the ultraviolet rest frame. In addition to the spectral coverage and sensitivity, the combination of high multiplexing and high density of fibres on sky will enable MOONS to identify a broad range of galaxy environments, from clusters to groups, filaments, and voids (Figure 3), and will unambiguously determine how galaxy properties depend on the environment in which they live.

Within the MOONS GTO, 190 nights are dedicated to the extragalactic survey MOONRISE (MOONS Redshift-Intensive Survey Experiment). With MOONRISE we expect to obtain key spectroscopic information for a few hundred thousand galaxies, possibly up to about half a million galaxies at $0.9 < z < 2.6$, as well as for a few thousand galaxies around the epoch of reionisation ($z \sim 6$–8). Such large statistics will also provide an unprecedented test of assumptions embedded in various cosmological simulations and models. Indeed, different models and simulations implement various physical processes in different ways in order to reproduce galaxy evolution and therefore they predict different galaxy properties in the early phases of their formation, which can be tested with MOONRISE's with unprecedented statistics.

Together with the MOONRISE GTO programme, during the first ten years of operation additional open time surveys will expand the legacy of MOONS to include millions of galaxy spectra spanning even broader redshift intervals and sampling a broader parameter space. In the following, we focus on the science goals and strategy of the MOONRISE survey, bearing in mind that this is only a sample of what MOONS will be able to deliver over the longer term.

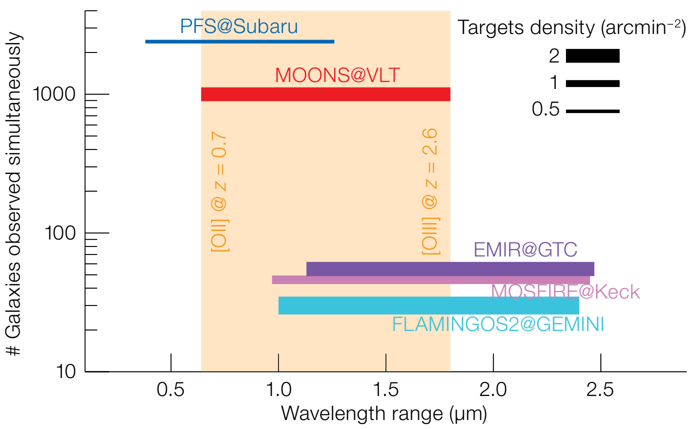

Figure 1. Comparison between MOONS and other near-infrared multi-object spectrographs at ground-based 8–10-m telescopes in terms of wavelength range, multiplexing and maximum target density that can be observed in a single pointing.

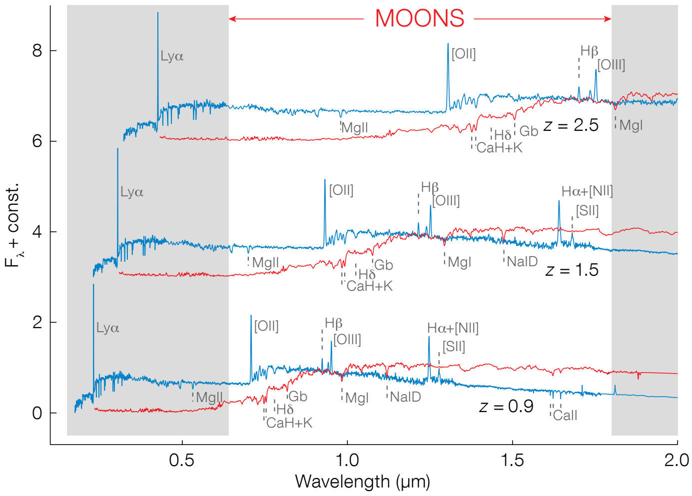

Figure 2. Examples of star-forming (blue) and passive (red) galaxy spectra shifted to three representative redshifts that will be targeted by the MOONRISE survey (Table 1), illustrating the observability of some of the primary nebular and stellar rest-frame optical features.

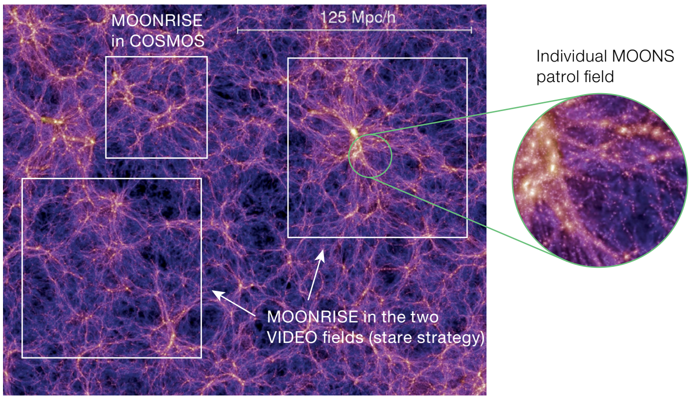

Figure 3. Example of different environments that will be sampled by the MOONRISE survey at a representative redshift slice around $z = 1.4$ by exploiting the large-scale dark matter distribution obtained from the Millennium simulation (Springel et al., 2005).

MOONRISE science goals

It is impossible to present an exhaustive list of the various cutting-edge science goals of the MOONRISE survey in the limited space available here. In the following, we outline a representative sample of the primary science aims of the survey.

- The metallicity evolution of galaxies. By measuring multiple nebular transitions in galaxies, spanning more than three orders of magnitude in mass ($10^{8.5} < M_{*}/M_{\odot} < 10^{11.7}$) and more than three orders of magnitude in the star formation rate (SFR), it will be possible to measure the gaseous metallicity for hundreds of thousands of galaxies, enabling us to solidly assess the evolution of the metallicity scaling relations. In particular, the redshift evolution (or lack thereof) of the mass-metallicity relation (for example, Troncoso et al., 2014; Kashino et al., 2019) and of the Fundamental Metallicity Relation (the relation between mass, SFR and metallicity; Mannucci et al., 2010) are still open and hotly debated problems. These are also key correlations predicted by various cosmological simulations (Maiolino & Mannucci, 2019). MOONS will measure these scaling relations and their scatter at $z \sim 1$–2 with unprecedented accuracy (Figure 4). Stellar metallicities will also be measured for tens of thousands of galaxies individually and for hundreds of thousands of galaxies through stacking, which will provide further tight constraints to galaxy evolutionary scenarios (for example, Trussler et al., 2019; Cullen et al., 2019).

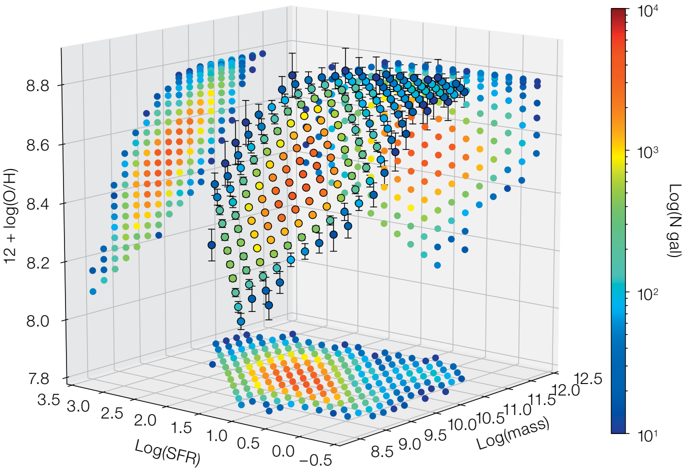

Figure 4. Three-dimensional diagram illustrating the capability of the MOONRISE survey to determine the shape of the fundamental metallicity relation — the relation between metallicity, mass and star formation rate — at $z \sim 1.5$, by measuring the metallicity of hundreds of thousands of galaxies. The colour coding gives the number of galaxies in each bin of mass and SFR. Galaxies are only included in this plot when metallicity can be determined by at least two independent indicators.

- Chemical abundances. Nebular and stellar features will enable us to investigate the relative abundance of chemical elements produced on different timescales (for example, N/O, α/Fe) for several thousands of galaxies and, through stacking, for up to hundreds of thousands of galaxies at high redshift. These relative chemical abundances will provide key information on the evolutionary timescales of primeval galaxies, on the efficiency of star formation, and on gas flows in and out of galaxies (Vincenzo et al., 2016; Thomas et al., 2010; De Lucia et al., 2017; Pipino et al., 2008).

- Active galactic nuclei and black hole demographics. MOONS's broad spectral coverage will allow us to trace the excitation diagnostics (for example, the BPT diagnostic [see Baldwin, Phillips & Terlevich, 1981], and high-ionisation species, such as HeII) across a broad redshift range encompassing the Cosmic Noon. It is expected that the MOONRISE survey will identify at least a few tens of thousands of type 2 AGN, including those which are completely absorbed in X-rays (Compton thick), down to Seyfert-like luminosities. This will enable us to unambiguously assess if and how black hole accretion correlates with star formation, with galaxy interactions or with the galaxy transition to quiescence. Comparing these results with cosmological simulations will allow us to understand the reciprocal role played by black hole accretion in galaxy formation, and vice versa. MOONRISE will also identify a few thousand type 1 AGN for which we will be able to measure the black hole mass by using the same methodology as in local type 1 AGN (virial relations calibrated on the broad component of Hβ and/or Hα). As a consequence, it will be possible to obtain an unprecedented census of black holes at high redshift, down to low masses (for those Seyfert 1's accreting close to their Eddington limit).

- Kinematics. The excellent spectral resolution of MOONS ($R \sim 7000$ in the H band) will enable a detailed analysis of the velocity profile of the stellar and nebular lines that is much more accurate than what can be achieved by the more modest resolution of SDSS or GAMA. The velocity dispersion will provide basic information on the dynamical mass down to low-mass systems and it will make it possible to explore the cosmic evolution of dynamical scaling relations such as the fundamental plane. The profile of the nebular emission and absorption lines (for example, [OIII], Hα, NaDI) will allow us to trace the demographics of galactic outflows, their physical properties and their relation with star formation rate, with galaxy mass, and with the presence of an AGN, which are key phenomena responsible for suppressing or possibly boosting star formation in galaxies (for example, Cicone et al., 2016; Concas et al., 2017, 2019; Nedelchev et al., 2019; Gallagher et al., 2019).

- Passive galaxies, galaxy transformation and star formation histories. Thanks to the high spectral resolution of MOONS it will be possible to mask the strong OH sky lines and rebin the spectrum to a resolution optimised to detect the continuum of each galaxy while preserving the information on the various stellar features (Figure 5). The spectroscopic characterisation of the stellar continuum along with the properties of the nebular emission lines (either absent or not associated with star formation) will unambiguously confirm candidate passive galaxies at high redshift (Citro et al., 2016; Merlin et al., 2019). The cosmic evolution of the fraction of passive galaxies is one of the most fundamental aspects required for the understanding of galaxy evolution, as it constrains the onset and mechanisms of star formation quenching in galaxies. Detecting the stellar continuum with high S/N will enable us to constrain the age and star formation history of galaxies (for example, Trussler et al., 2019; Carnall et al., 2019; Wild et al., 2020). This will be particularly interesting for galaxies in the so-called green valley — galaxies in transition from the star formation Main Sequence to quiescence — as it will enable us to trace the timeframe of the quenching process in galaxies. With the observing strategy envisaged for MOONRISE we expect to detect the continuum of thousands of individual passive galaxies down to $H_{AB} < 22$ and, through stacking, of tens of thousands of passive galaxies down to at least $H_{AB} < 23$. In the case of star-forming and green-valley galaxies (for which the detection of — some —

nebular emission lines will facilitate the determination of the spectroscopic redshift) stacking will be possible down to $H_{AB} = 25$.

- The role of the environment. Huge statistics, high target density, near-infrared spectral coverage and high sensitivity make MOONS the optimal machine to determine and characterise the environment in which high-z galaxies live and to tackle one of the key open problems in galaxy evolution, namely if, how and when environment has affected galaxy evolution and galaxy properties.

  The MOONRISE survey is expected to explore the environment of galaxies at $z \sim 1$–2 over four orders of magnitude in terms of galaxy overdensity (from $\log(1+\delta) \sim -2$ to $\log(1+\delta) > 2$), i.e., from voids to (proto-)clusters. The observing strategy will allow us to identify groups, derive their halo masses and disentangle central galaxies from their satellites. It will also be possible to trace filaments connecting tens of (proto-)clusters. By combining this environmental outcome with the information on galactic properties obtained with the same MOONS spectra it will be possible to assess with unprecedented accuracy whether different environments accelerate or inhibit galaxy evolution and galaxy transformation, and to determine the different evolutionary paths of central and satellite galaxies. As an example, Figure 6 illustrates how the MOONRISE survey will be able to discriminate between the effects of environmental and mass quenching at $z \sim 1.5$, comparable to local SDSS studies (Peng et al., 2010). Moreover MOONRISE will give access to the phase-space distribution from the core to the outskirts of clusters/groups, which will provide an unprecedented view of the evolution of galaxy physical properties with respect to their infall history in their host, for a variety of halo masses.

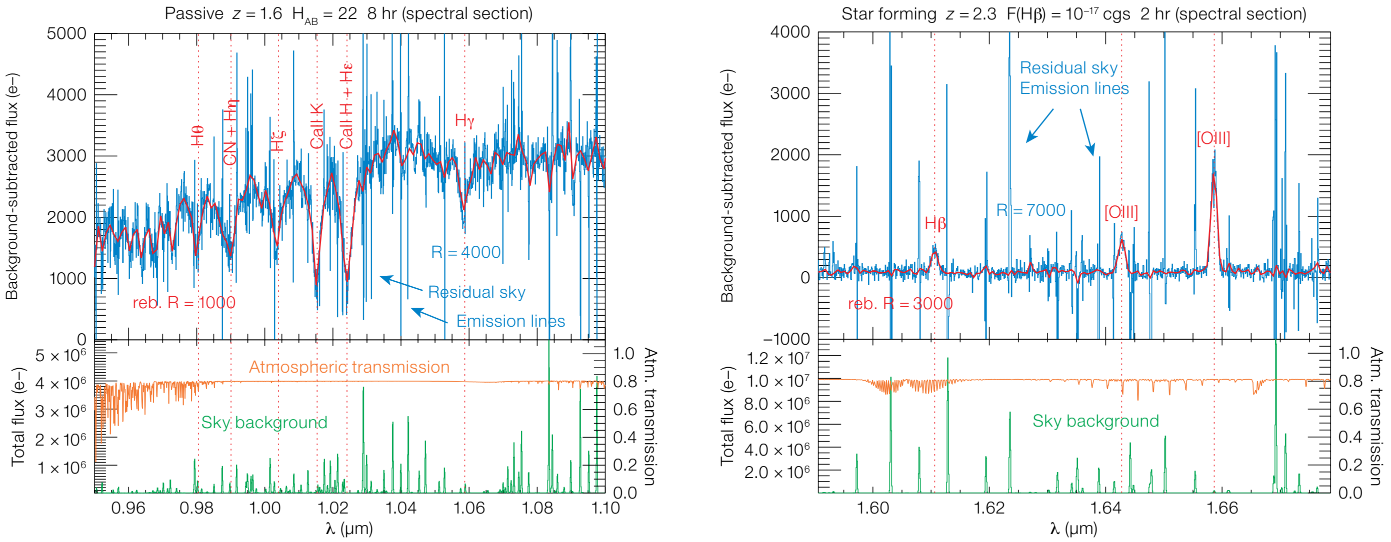

Figure 5. Portions of MOONS simulated spectra of a passive galaxy ($H_{AB} = 22$) at $z = 1.6$ (left) observed for 8 hours on source and a star forming galaxy ($F(\mathrm{H}\beta) = 10^{17}$ erg s^{-1} cm^{-2}, $H_{AB} = 23.5$) at $z = 2.3$ (right) observed for two hours on source. The bottom panels show the total observed spectrum (green), including sky emission, and the atmospheric transmission (brown). The top panels show the background-subtracted spectrum (blue) and the same spectrum rebinned to lower resolution after masking the OH sky lines (red).

- Galaxies at the dawn of the Universe. While performing the primary survey of galaxies at Cosmic Noon, a fraction of the fibres will be allocated to observing in depth galaxies probing the Cosmic Dawn. Specifically, we expect to obtain deep spectra of a few thousand galaxies at $z \sim 5$–10. The MOONS sensitivity, combined with its spectral resolution, is expected to provide key information on the visibility and shape of the Lyα line, which in turn provides precious information on the amount of neutral gas in the intergalactic medium and on the escape fraction of ionising photons. MOONS will also have enough spectral coverage to measure various other lines in the ultraviolet rest frame portion of the spectra (CIV, HeII, CIII], NV), which will provide key information to identify primeval AGN and to determine metal enrichment, hardness of the ionising radiation and ionisation parameter in these primeval systems; these are all key quantities that will be compared with predictions of galaxy formation scenarios and reionisation models.

Survey strategy

The GTO team has been working on a reference survey that is expected to deliver the statistics, depth and area appropriate to achieving the goals discussed above, as well as tackling many more science cases.

We will target three main fields: the Cosmic Evolution Survey field (COSMOS) and the two fields XMM-LSS and ECDFS from the VISTA Deep Extragalactic Observations (VIDEO) Survey (see Jarvis et al., 2013). Together with the Galactic survey, these fields will enable an efficient scheduling of the GTO. We plan to observe 1 square degree in COSMOS (part of the area covered more extensively in multiple bands, see Laigle et al., 2016 and Nayyeri et al., 2017), and 3 to 6 square degrees in the other two fields depending on the observing mode, as discussed in the following.

Targets will be selected from multi-band optical to near-infrared photometry in

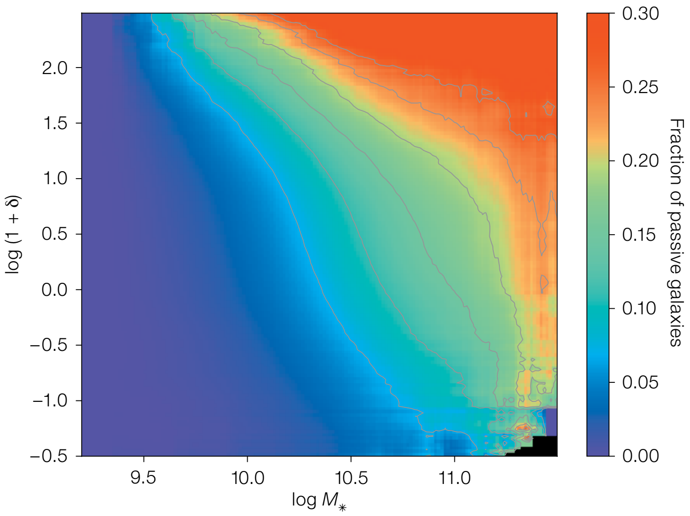

Figure 6. Fraction of passive galaxies as a function of galaxy overdensity and as a function of galaxy mass for satellite galaxies at $1.3 < z < 1.8$ from the simulated MOONRISE survey at $H_{AB} < 23$ (assuming completeness of 70% over an area of 6 square degrees).

the three main (photometric) redshift ranges listed in Table 1 in which most of the primary optical nebular lines, as well as primary optical stellar features, are observable in the MOONS band (Figure 2) and also avoiding significant overlap with other MOS spectrographs at 8-m telescopes (for example, PFS at Subaru can observe Hα out to $z = 0.9$). As some of the science cases require high completeness over a mass-limited sample while other science goals require large statistics on a magnitude-limited sample, we have applied a double selection whereby in each redshift bin galaxies are selected through their mass *or* their magnitude as listed in Table 1, corresponding to about 6000 targets per MOONS patrol field, allowing an efficient allocation of the 1000 fibres.

High completeness is required for many science cases discussed above, especially for properly assessing the environment, and can be achieved by observing the same pointing several times with different fibre configurations. Obviously, with this strategy the efficiency of allocating fibres to new targets gradually decreases (as the density of unobserved targets rapidly decreases), therefore a compromise between survey efficiency and completeness has to be achieved. In the current survey design we aim at achieving a completeness of 80% in the COSMOS field and 70% in the two VIDEO fields. The number of repeated observations required to achieve these levels of completeness will depend on whether observations have to be performed in Xswitch mode (i.e., ~ 400 pairs of fibres allocated to targets and sky for nodding observations) or in Stare mode (i.e., ~ 900 fibres allocated to targets while the background is sampled through a few tens of fibres scattered over the patrol field; see Cirasuolo et al., p. 10). These allocation efficiencies are conservative and take into account potential limits associated with the fibre allocation algorithms. Whether the Stare mode gives an acceptable background subtraction or we need to resort to using the more traditional but less efficient Xswitch nodding mode will only be assessed at the telescope.

The detection of nebular emission lines in star-forming galaxies, even in systems as faint as H_{AB} ~ 25 (in the mass-limited samples), can be achieved much more quickly than for the stellar continuum in passive galaxies. Our baseline strategy is to allocate 25% of the fibres to passive galaxies for each pointing, which will be repeatedly observed for a total of 8 hours on source, while at the same time all other fibres are reallocated to different star-forming galaxies, which will be observed with exposures of 1 or 2 hours (the relative fraction of fibres allocated to passive and star-forming galaxies stems from the relative density on sky of these two populations). With this strategy, in COSMOS we will observe (in Xswitch mode) ~ 480 passive galaxies and ~ 4350 star-forming galaxies in each MOONS pointing (resulting in the desired 80% completeness) for a total observing time of 38 nights, including overheads and allowance for bad weather. These figures nearly double if the Stare observing mode can be adopted. In the VIDEO fields we will adopt fewer repeated observations resulting in a lower completeness of 70%. Given the multiple passes in each pointing to reach completeness, a subset of targets will be observed multiple times, with integrations up to 40 hours on source.

As mentioned earlier, a few tens of fibres in each pointing will be allocated to candidate galaxies at $z > 5$, identified via broad-band photometry through the Lyman-break technique or as Lyman-α emitter candidates identified in narrow-band surveys. Each of these high-*z* galaxies will be observed with integrations of 8 hours each. A similar allocation of a few tens of fibres per field is also being considered for X-ray-selected AGN, while additional AGN will be identified among the magnitude/mass selected samples through their nebular line diagnostics.

			Number of galaxies*	
Redshift range	Main spectral features	Selection	Xswitch (4 square degrees)	Stare (7 square degrees)
$0.9 < z < 1.1$	[OII], Hβ, [OIII], Hα, [NII], [SII]	$H_{AB} < 23$ or	33 900	75 300
	CaH+K, Hδ, Gb, Mgb, NaID, CaII	$\log(M_*) > 9.5$	12 900	28 500
$1.2 < z < 1.7$	[OII], Hβ, [OIII], Hα, [NII], [SII]	$H_{AB} < 23.5$ or	88 700	197 100
	MgII, CaH+K, Hδ, Gb, Mgb, NaID	$\log(M_*) > 9.5$	13 700	30 500
$2.0 < z < 2.6$	[OII], Hβ, [OIII]	$H_{AB} < 24$ or	54 500	121 100
	MgII, CaH+K, Hδ, Gb, Mgb	$\log(M_*) > 10$	2100	4700
$5 < z$	Lyα, NV, HeII, CIV, CIII]	$H_{AB} < 26$	2000	4500
Total			207 800	461 700

Table 1. Summary of the MOONRISE survey design. The blue numbers represent star-forming galaxies and AGN and the red numbers are passive galaxies.

The total number of galaxies expected to be observed in MOONRISE is given in Table 1.

We would, however, like to emphasise that the survey design is still being optimised by taking into account the analysis of photometric samples and mock samples that are being refined, as well as the optimisation of the fibre allocation software and the eventual performance of the instrument on sky.

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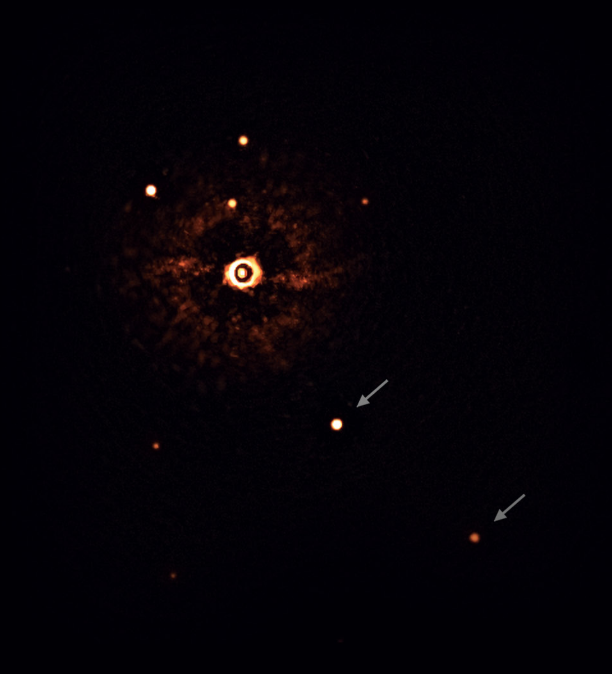
ESO/Y. Beletsky

A celestial conjunction, involving the Moon, Venus and Jupiter, shines above one of the VLT Unit Telescopes and an Auxiliary Telescope.



ESO/Bohn et al.

This image, captured by the SPHERE instrument on the VLT, shows the star TYC 8998-760-1 accompanied by two giant exoplanets which are visible as two bright dots in the centre (indicated by arrows). The planets appear similar to other bright dots in the image, which are background stars. By taking different images at different times, the planets could be distinguished from the background stars by their movement. The bright and dark rings on the star's image are optical artefacts.

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The ALPINE–ALMA [CII] Survey: Exploring the Dark Side of Normal Galaxies at the End of Reionisation

Matthieu Béthermin[1]
Miroslava Dessauges-Zavadsky[2]
Andreas L. Faisst[3]
Michele Ginolfi[2]
Carlotta Gruppioni[4]
Gareth C. Jones[5,6]
Yana Khusanova[1,7]
Brian Lemaux[8]
Peter L. Capak[3,9,10]
Paolo Cassata[11,12]
Olivier Le Fèvre[1]
Daniel Schaerer[2]
John D. Silverman[13,14]
Lin Yan[15]
and the ALPINE collaboration

[1] Aix Marseille Université, CNRS, CNES, LAM, Marseille, France
[2] Département d'Astronomie, Université de Genève, Versoix, Switzerland
[3] IPAC, M/C 314-6, California Institute of Technology, Pasadena, USA
[4] INAF – Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Italy
[5] Cavendish Laboratory, University of Cambridge, UK
[6] Kavli Institute for Cosmology, University of Cambridge, UK
[7] Max-Planck-Institut für Astronomie, Heidelberg, Germany
[8] Department of Physics, University of California Davis, USA
[9] The Cosmic Dawn Center (DAWN), University of Copenhagen, Denmark
[10] Niels Bohr Institute, University of Copenhagen, Denmark
[11] Dipartimento di Fisica e Astronomia, Università di Padova, Italy
[12] INAF – Osservatorio Astronomico di Padova, Italy
[13] Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), The University of Tokyo, Kashiwa, Japan
[14] Department of Astronomy, School of Science, The University of Tokyo, Japan
[15] The Caltech Optical Observatories, California Institute of Technology, Pasadena, USA

Cold gas and cosmic dust are the fuel of star formation. ALPINE is an ALMA Large Programme which has built the first statistically representative sample of star-forming galaxies in the adolescent Universe by targeting emission from singly ionised carbon [CII] at 158 µm, which traces both emission from star-forming regions and molecular hydrogen gas clouds, and the thermal continuum from dust at the end of the epoch of reionisation ($4.4 < z < 5.9$). Observations by the ALPINE team have revealed that a significant fraction of the star formation at this epoch is already hidden by dust clouds. ALPINE observations have also shown how unruly these young galaxies were by finding a large fraction of mergers and ubiquitous gas outflows.

Description of the survey

The aims of the ALPINE survey

Before the inception of the Atacama Large Millimeter/submillimeter Array (ALMA), the main constraints on the evolution of galaxies in the adolescent Universe ($4 < z < 6$) came from rest-frame ultraviolet (UV) light that was redshifted to optical and near-infrared wavelengths. Thanks to its unprecedented sensitivity in the infrared, ALMA has opened a new window through which to explore the cold and dusty Universe at these early times. Pioneering studies demonstrated that ALMA can detect both the dust continuum and the far-infrared (FIR) fine-structure line [CII] (see, for example, Capak et al., 2015). Continuum and line emission can be targeted simultaneously with ALMA and are both valuable tracers of dust-obscured star formation. ALPINE (the ALMA Large Programme to INvestigate [CII] at Early times; Le Fèvre et al., 2020; Faisst et al., 2020; Béthermin et al., 2020) builds the first comprehensive, statistically representative, multi-wavelength sample of normal (main-sequence) star-forming galaxies at the end of the epoch of reionisation, with observations of all galaxies in the sample from the rest-frame UV to the far-infrared. In total, 118 spectroscopically selected galaxies at redshifts of $4.4 < z < 5.9$ were observed as part of the ALPINE survey.

The main goals of this survey are:
- To test the [CII] line as a star formation tracer at high redshift, since some theoretical models predict a deficit in [CII] per unit star formation in the low-metallicity galaxies that dominate at high redshift as compared to the local SFR-[CII] relation.
- To use both the dust continuum and [CII] to estimate the contribution of obscured star formation in known spectroscopic sources at $4 < z < 6$, and to use this estimate to understand how this contribution modulates the total star formation rate density at these epochs.

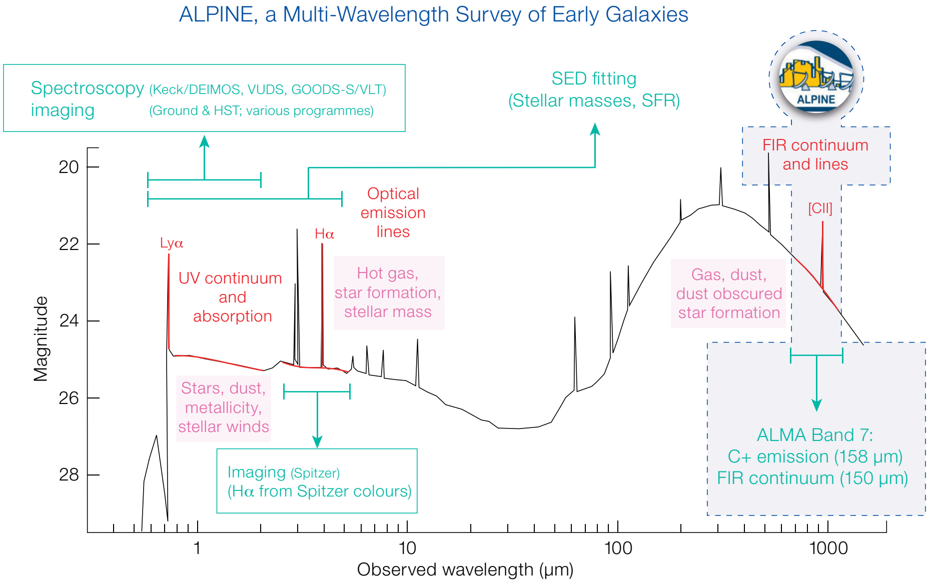

Figure 1. UV-to-millimetre spectrum of a galaxy and illustration of the various features probed by ALPINE and ancillary data (figure from Faisst et al., 2020). The spectrum sketch is based on a typical $z = 5$ galaxy.

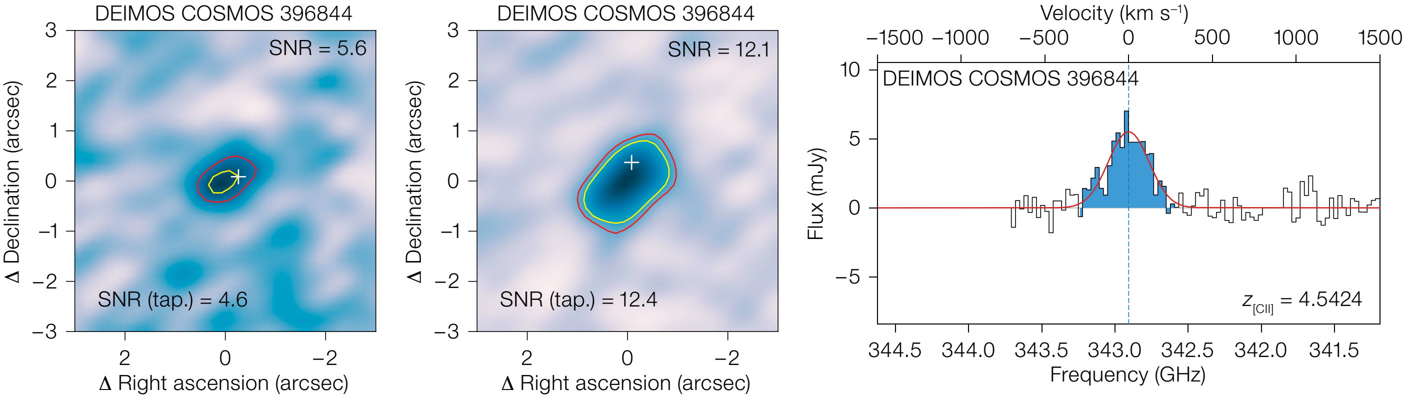

Figure 2. Example from ALPINE of continuum map (left), [CII] map (moment-0; centre), and [CII] spectrum (right). The source is DEIMOS_COSMOS_396844, adapted from Béthermin et al., 2020).

- To estimate the precise relationship between the stellar mass of a galaxy and its star-formation activity at $4 < z < 6$ by combining UV (emission tracing exposed young stars) and infrared (emission tracing young stars hidden by dust) data to estimate the total star formation rate (SFR).
- To understand the basic interstellar medium (ISM) properties of these systems from their dust and [CII] luminosities.
- To measure the dynamical masses of these systems using [CII] to constrain their gas fractions.
- To measure the merger rate using the velocity and position information of [CII].
- To identify and quantify possible gas outflows from the [CII] line profiles.

Sample selection and ancillary data

The ALPINE sample is primarily rest-frame UV-limited at $M_{1500} < -20.2$, a limit which corresponds to galaxies about 2.5 times fainter than those typical at this epoch (i.e., $L_{\ast,\mathrm{UV}}$). This limit naturally leads to a sample selected to an SFR limit of $\gtrsim 10\ M_\odot\ \mathrm{yr}^{-1}$. We found that this cut maximises the sample size while simultaneously minimising the amount of observing time with ALMA. To set the expectations of the ALMA observations, the [CII] emission fluxes were conservatively predicted using the relation between the observed UV luminosity and [CII] line emission based on a pilot sample by Capak et al. (2015). Because of ALMA's narrow frequency bands, the redshifts of all targeted galaxies were already determined precisely by one of several large spectroscopic surveys on the targeted legacy fields (COSMOS and ECDFS). Most of the spectroscopic redshifts were measured from observations taken as part of the VUDS survey (Le Fèvre et al., 2014) and the Keck/DEIMOS 10k survey (Hasinger et al., 2018). To mitigate potential biases associated with spectroscopic selections, the target sample was selected by several different methods, for example, via colours (Lyman-break dropout technique), narrow bands (Lyα emission selection), photometric redshifts, and serendipitous detections. Furthermore, the spectroscopic redshifts are derived from UV absorption lines as well as the Lyα emission feature. In total, 13 target galaxies are located in the ECDFS field (from the VISTA Deep Extragalactic Observations survey, VIDEO) and 105 in the COSMOS field from Cosmic Evolution Survey. As shown in Faisst et al. (2020), the ALPINE galaxies represent the average population of galaxies at these redshifts well in terms of the mass of their stellar content and SFRs. As such, ALPINE observations enable, for the first time, the study of the panchromatic properties of the average galaxy at these cosmic times with a high degree of statistical certainty.

The ALPINE team combined ALMA observations in the far-infrared with a wealth of exquisite ancillary imaging and spectroscopy products at rest-frame UV and optical wavelengths, all of which constitutes the first large multi-wavelength survey of galaxies at these redshifts (Figure 1). All galaxies have deep photometry from UV to near-infrared (NIR) from ground-based telescopes, the Hubble Space Telescope, and the Spitzer Space Telescope. These data allow accurate constraints of galaxies' physical properties (stellar mass, SFR, age) from high-quality spectral energy distribution (SED) fitting. In addition, the Spitzer [3.6 μm]–[4.5 μm] colours provide estimates of their Hα emission strength, hence additional constraints on their rates of star formation. The deep rest-frame UV spectroscopy available for all galaxies provides valuable insights into the metallicity and stellar wind properties via UV absorption lines and the Lyα emission line. Furthermore, the UV continuum slope is a good measure of dust opacity along the line of sight and can, together with the ratio of far-infrared to UV luminosity, constrain the dust properties of these galaxies. The ancillary imaging and spectroscopic data, as well as various measurements of physical parameters, are detailed in Faisst et al. (2020).

ALMA observations and achieved performance

The ALPINE targets were selected to have a redshift in which [CII], if present, was observable by ALMA's band 7. Owing to low atmospheric transmission, redshifts of $4.6 < z < 5.1$ were excluded. We used the two most compact configurations to maximise the sensitivity of the integrated flux and in order to detect extended [CII] and far-infrared continuum emission. To minimise the calibration overheads, we grouped our sources by pairs of galaxies with similar redshifts in order to observe them with the same correlator tuning.

ALPINE was mainly observed during Cycle 5, between May and August 2018.

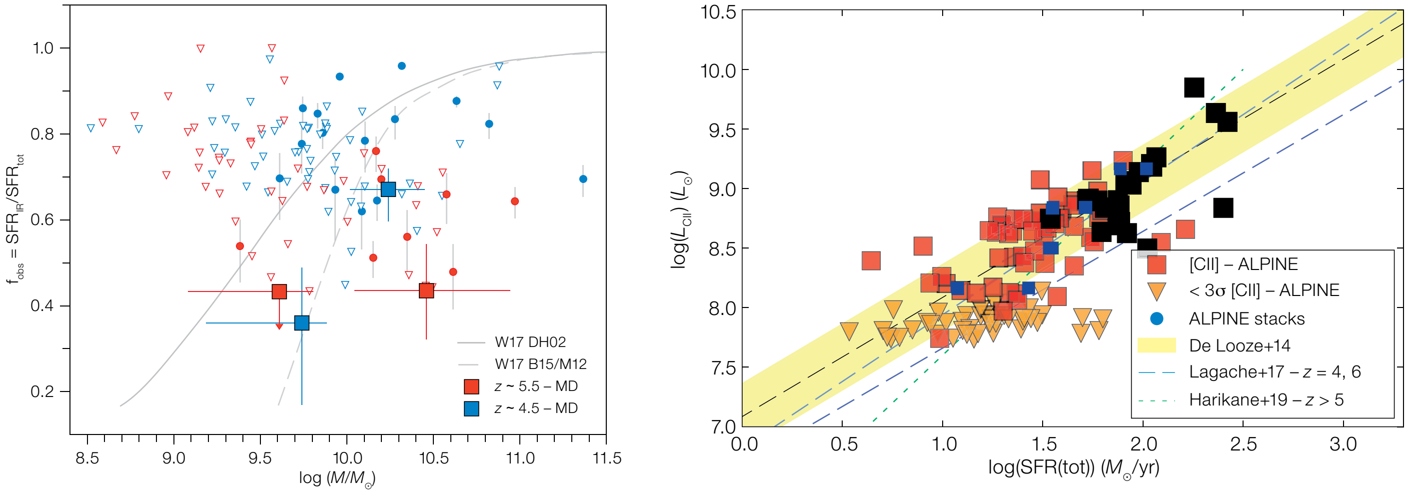

Figure 3. Left panel: Obscured star formation rate fraction as a function of stellar mass (from Fudamoto et al., in preparation). The blue symbols correspond to the $z \sim 4.5$ redshift bin and the red ones to $z \sim 5.5$. The large filled squares are measured by stacking. The filled circles and the empty downwards triangles are the individual detections and upper limits from non-detections, respectively. ALPINE results demonstrate that massive systems are already significantly dust obscured at $z > 4$. Right panel: Relation between the [CII] luminosity and the star formation rate (from Schaerer et al., 2020). The black squares are the continuum ALPINE detections, the red squares the data points for which we used the UV-slope to derive their SFR, and the orange downward triangles are the non-detections. The blue dots show the mean relation estimated by stacking ALMA data to measure the average obscured SFR (Béthermin et al., 2020).

However, 18 sources were carried over into Cycle 6 and were observed in January 2019. All the data were analysed using a homogeneous imaging and source extraction procedure. We reached an average sensitivity of 29 µJy in continuum and 0.14 Jy km/s in [CII]. The mean beam size is 0.85 × 1.13 arcseconds.

We detected 23 sources (19.5%) in continuum and 75 (63.5%) in [CII] at > 3.5σ. In addition, we detected 56 other continuum sources around the ALPINE targets serendipitously. The observations, the data processing, and the construction of the catalogue are described in detail in Béthermin et al. (2020). Figure 2 illustrates an example of an ALPINE continuum and [CII] detection.

Dust-obscured star formation in the adolescent Universe

Massive galaxies already contain a lot of dust

Observations of high-redshift galaxies are traditionally limited to rest-frame UV wavelengths and, if dust is present, are therefore strongly affected by obscuration. Generally, it is assumed that galaxies in the early Universe contain very little amounts of dust as the dust content must be built up over time. With ALPINE, we can directly measure the dust content and fraction of obscured UV light in a large sample of $4 < z < 6$ galaxies (Fudamoto et al., in preparation) that span over an order of magnitude in stellar mass and SFRs. Overall, the ALPINE data confirm the drop in dust attenuation at high redshifts relative to similar galaxies at lower redshifts and show that galaxies at high redshifts can be, on average, characterised by a dust attenuation parametrisation similar to that found in the metal-poor Small Magellanic Cloud.

Compared to lower redshifts, where the dust attenuation in galaxies is typically found to be characterised well by those properties of local starburst galaxies, the different parametrisation seen in high-redshift galaxy populations means that, for a given line-of-sight dust extinction measured by the UV continuum slope, less far-IR emission is emitted (resulting in a lower UV to far-IR luminosity ratio). However, ALPINE data also show that massive galaxies, i.e., $\log(M_*/M_\odot) > 10$, have already established a considerable dust content in a short time, less than 1 billion years after the Big Bang. Specifically, single far-IR-detected galaxies show dust obscured SFR fractions of > 40%, which is consistent with galaxies of the same mass at redshifts $z < 2.5$ (Figure 3 left). These observations put important constraints on the timescale of, and thus the mechanisms related to, dust formation in some of the most massive galaxies in the early Universe.

The ionised carbon [CII] line as a tracer of star formation

The [CII] emission has been shown to trace the SFR of galaxies in the nearby Universe well up to $z \sim 2$ (De Looze et al., 2014). It is debated whether this is also the case in the early Universe. Combining ALPINE data with earlier ALMA observations from the literature, the [CII]-SFR relation in the Early Universe was explored for the first time with a statistically representative sample of > 150 star-forming galaxies at $z \sim 4$–8 (Schaerer et al., 2020 and see Figure 3, right). To do this analysis, the SFR of the galaxies must be estimated correctly. For galaxies detected in the far-infrared continuum, the obscured SFR derived from the far-infrared can be combined with the unobscured SFR measured from the UV continuum emission to yield the total SFR. For the sources not detected in far-infrared continuum, various methods to derive the SFR from ancillary data only have been tested and shown to provide consistent results (UV continuum corrected from dust attenuation using its slope or SED-derived SFR of rest-frame UV to near-IR data). Taking into account upper limits on the total SFR, our galaxies show a [CII]-SFR relation comparable to the local one, and hence do not suggest a significant evolution of this relation over the last 13 Gyr of cosmic time. This is an important verification that [CII] can be used to trace the total SFR up to $z = 6$.

A non-negligible fraction of light from star formation is already hidden in dust clouds

With ALPINE, we are able to estimate the evolution of the dust-hidden star formation rate density (SFRD) beyond a redshift of 4 with two complementary methods. First, we stacked the far-infrared continuum data (of detected and non-detected ALPINE galaxies) to estimate the dust-hidden SFRD contributed by a UV-selected sample. We find that, even at a redshift of $z = 5.5$, the dust-obscured SFR is significant and contributes up to 50% of the total SFRD for this population alone (Figure 4 and Khusanova et al., in preparation). However, such an analysis does not speak to the total amount of dust-enshrouded star formation at these epochs. The second contribution comes from galaxies that are faint or undetected in the UV, but which shine primarily at far-infrared wavelengths. In order to quantify the contribution from this population, we searched for galaxies within our ALMA observations that were detected in the far-infrared continuum (Béthermin et al., 2020; Gruppioni et al., in preparation) and/or the [CII] line (Loiacono et al., in preparation). These populations allowed us to study the contribution of the SFRD by dusty UV-faint galaxies at $z > 4$.

As shown in Figure 4, the SFRD from these ALPINE non-target continuum detections shows a flat distribution over the whole 0.5–6 redshift range, with no significant decrease beyond the Cosmic Noon ($1 < z < 3$). The high value of the SFRD at $z = 5$ is also confirmed by the results obtained for the [CII] serendipitous detections. By combining the results of the two methods, along with the UV-based redshift evolution of the SFRD, it is possible to map the total evolution of the SFRD at these redshifts.

The total SFRD as measured by ALPINE data is in agreement with those from previous far-IR and radio surveys, but higher than those estimated from optical/UV surveys at $z > 3$. The measured difference from the UV results is observed to increase with redshift and peaks at $z = 6$, where the observed excess is about a factor of 10. This discrepancy implies that a considerable amount of star-formation activity at high redshifts is still missed by surveys sampling the UV rest frame. This significant and increasing contribution of dust-obscured activity cannot be recovered, even correcting the UV data for dust-extinction, and rather requires the addition of UV-faint galaxies selected in the IR. Similarly, current galaxy formation models and simulations are not able to predict such a high SFR in dusty galaxies as is observed in the ALPINE sample at early times.

The surprisingly complex life of galaxies at the end of reionisation

Star-formation-driven outflows and circumgalactic enrichment

Current models of galaxy formation broadly agree on the key importance of star formation feedback in regulating the evolution of galaxies across cosmic time. Intense episodes of star formation can induce supernova-driven winds that efficiently accelerate interstellar gas. Such processes eventually result in the expulsion of material from the disc, thus inhibiting future star formation and enriching the circumgalactic/intergalactic medium with heavy elements. However, to date, observational evidence for star-formation-driven outflows is still limited to galaxies observed in the local Universe and at intermediate redshifts.

Using the ALMA observations taken as part of the ALPINE survey, which were complemented by the previously described wealth of ancillary photometric/spectroscopic multi-wavelength data, we

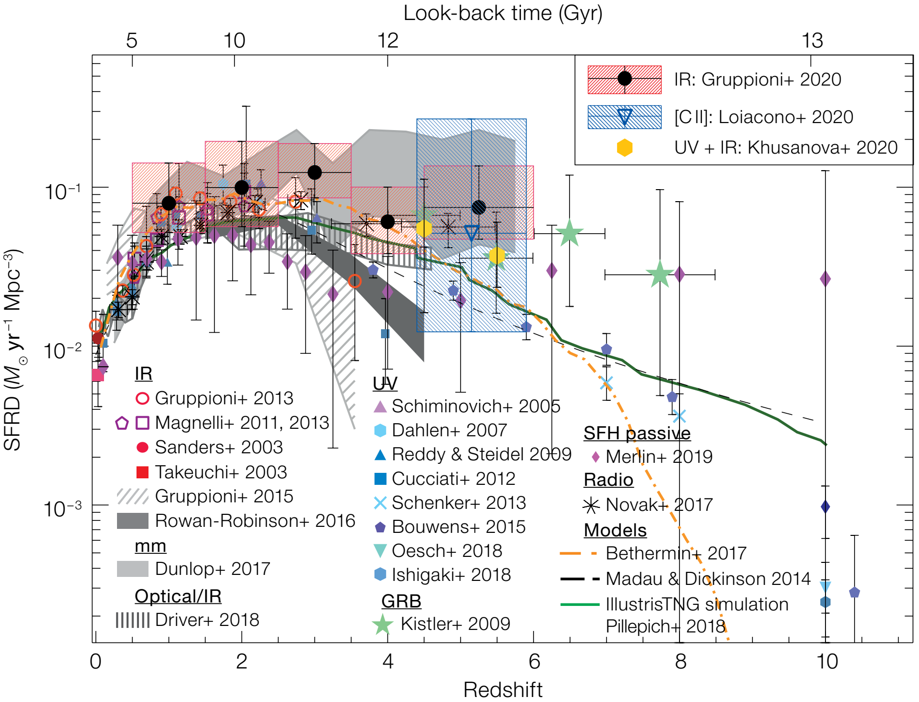

Figure 4. Redshift evolution of the comoving star formation rate density (SFRD), obtained from ALPINE: as in the legend, the orange boxes and black filled circles are the derivations from continuum non-target sources (Gruppioni et al., in preparation), the blue box and blue open triangle are from serendipitous [CII] detections (Loiacono et al., in preparation), while the yellow filled hexagons are the UV+IR SFRD estimates based on the ALPINE targets (Khusanova et al., in preparation). For comparison, estimates from other surveys are shown as grey shaded areas and open or filled symbols, as described in the legend. The model from Madau & Dickinson (2014) is shown as a black dashed curve, while the prediction of the IllustrisTNG simulation is shown as a dark-green solid curve obscured at $z > 4$.

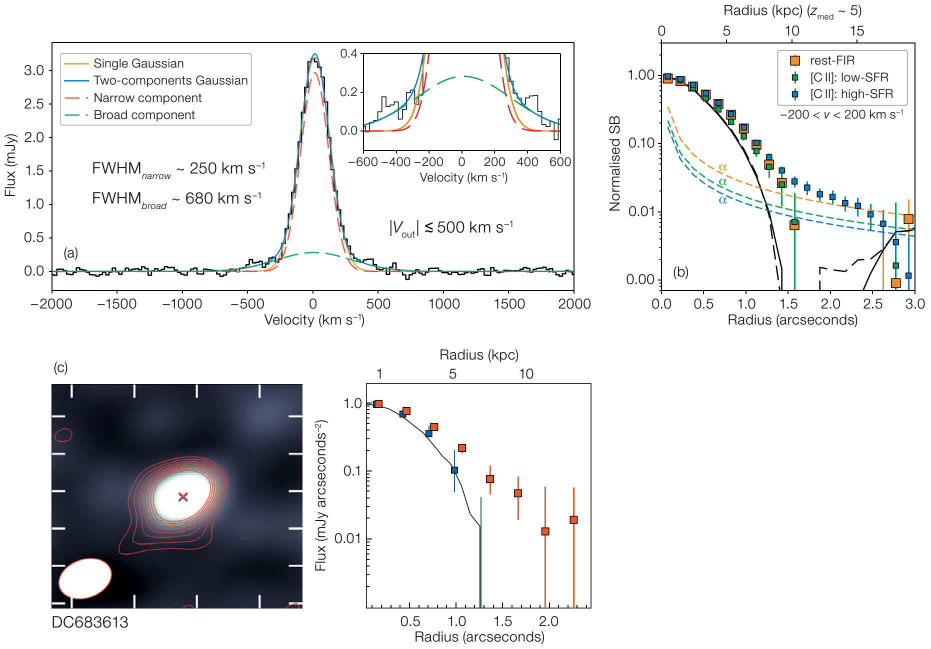

Figure 5. (a) Stacked [CII] spectrum of high-SFR (> 25 $M_\odot$ yr^{-1}) ALPINE galaxies, showing broad wings in the high-velocity tails, extending up to $|v| < \sim 500$ km s^{-1}. (b) Circularly averaged radial profile of the stacked [CII] line-core emission in highly star-forming galaxies (blue), extending to diameter scales > 20 kpc, compared with the analogue emission arising from lower-SFR galaxies (green) and the stacked far-infrared continuum. (c) Example of spatial distribution (map on the left and radial profile on the right) of [CII] (red contours and red squares) and rest-frame UV emission (grey-scale image and blue squares) in a galaxy showing a [CII] halo component.

conducted a number of pioneering studies on the efficiency of galactic feedback and the cycle of gas, dust, and stars in the early Universe.

By stacking the ALPINE [CII] spectra, we discovered signatures of outflows driven by feedback from massive stars. In ALPINE galaxies with high star formation, high-velocity tails of the stacked [CII] line profile revealed gas that was outflowing at velocities of a few hundred km s^{-1}, and, in extreme cases, up to about 500 km s^{-1}. These winds typically excise gas at a rate similar to the SFR of these galaxies. The relatively small amount of outflowing material suggests that feedback by star formation, while capable of regulating star formation to some extent, is not the dominant factor in the rapid quenching of high-z galaxies (Ginolfi et al., 2020a and Figure 5a), which necessarily must occur to explain the populations of passive galaxies with relatively old stellar ages observed at $z = 1$–3.

The [CII] line traces the velocity of cold gas in galaxies and is thus a good estimator of the velocity of the galaxy as a whole (also called the systemic redshift). We exploit this property and the available optical spectroscopy to explore the velocity offsets of UV rest-frame ISM lines. We find velocity blueshifts of the ISM lines in the range $-500 < \Delta v(\mathrm{ISM–[CII]}) < 0$ km s^{-1}, values which are consistent with the [CII] spectral stacking analysis discussed above, and which we interpret as further evidence of ubiquitous galactic outflows (Cassata et al., 2020; Faisst et al., 2020).

In the stacked ALPINE data cubes, we also detected [CII] halos extended on physical scales of > 20 kpc around galaxies with high star formation. Such halos likely originate from metal-polluted circumgalactic gas that was enriched by past outflows (Ginolfi et al., 2020a). We followed up this result by exploring sizes and extended halo structures in and around a subset of individual ALPINE galaxies. We show that sizes of galaxies in [CII] (i.e., their effective radii) are generally larger than those measured in the UV by up to a factor of 4. About one third of galaxies without an observed companion are surrounded by a [CII] halo component that is extended over a scale of 10 or more kpc. Consistent with the stacking analysis described above, ALPINE observations revealed that galaxies that host larger [CII] halos generally have higher stellar masses and star formation rates (Fujimoto et al., 2020 and Figure 6).

Altogether, our findings suggest that star-formation-driven outflows that deposit metal-enriched gas into the circumgalactic medium are highly prevalent in galaxies with higher SFRs at higher redshift, and that such processes already regulate star formation and the cycling of gas, dust and star formation in normal galaxies at very early epochs in the Universe.

The dynamic life of high-redshift systems

Since [CII] is emitted from multiple phases of the ISM, it makes an ideal tracer of the underlying kinematics of a galactic system. As a first step towards characterising the dynamics of the ALPINE galaxies, a group of astronomers within the collaboration examined a set of diagnostic plots (for example, integrated intensity, velocity field, position-velocity diagrams) created from the [CII] data cube of each source. From these diagnostic plots, galaxies were classified as rotators, mergers, extended dispersion-dominated systems (i.e., large galaxies whose kinematics exhibited primarily random motions), or compact dispersion-dominated galaxies. Of the 63 galaxies whose [CII] emission was bright enough to allow for classification, 9 (14%) were classified as rotators, 31 (49%) as mergers, 15 (24%) as extended dispersion-dominated, and 8 (13%) as compact dispersion-dominated (Le Fèvre et al., 2020). This kinematic diversity suggests that galaxies in this early epoch were not a dynamically homogeneous group but had already travelled various evolutionary routes. The large number of merging systems within the ALPINE sample suggests that mass assembly in high-redshift, star-forming galaxies is not only driven by *in situ* star-formation activity, but aided considerably by *ex situ* contributions.

For a few of the ALPINE galaxies in which merging activity is detected, the [CII] data allow us to probe the detailed kinematics of the system. In one such system, we find evidence for an ongoing major merger between two galaxies, with a third minor galaxy nearby (Jones et al., 2020). This configuration suggests that this system is the progenitor of the massive galaxies observed by $z \sim 2$. A different system reveals two major components and two minor components, surrounded by a significant [CII] halo (Ginolfi et al., 2020b), directly revealing the role of mergers in enriching the IGM of massive galaxies. We are currently improving upon this initial qualitative classification method using more systematic and homogeneous criteria (Jones et al., in preparation; Romano et al., in preparation).

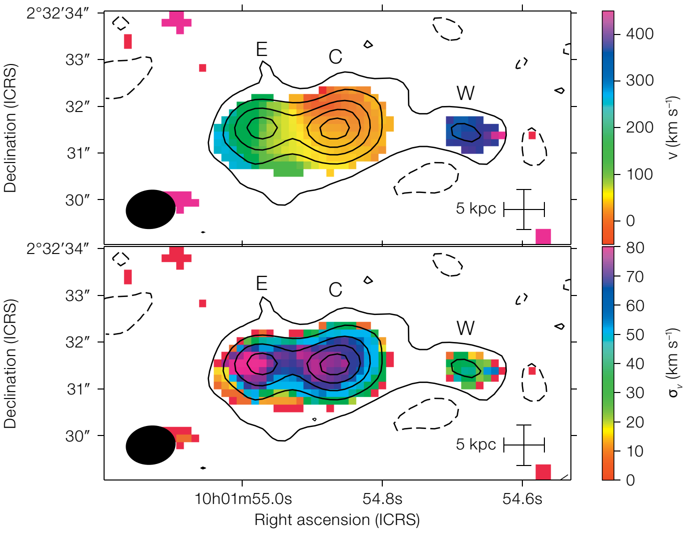

Figure 6. Velocity (upper panel) and velocity-dispersion maps of the triple-component merger DEIMOS COSMOS 818760 (Jones et al., 2020).

Large gas reservoirs of high-redshift systems

For 18 ALPINE galaxies classified as non-mergers and with size measurements, we were able to infer dynamical mass estimates, which probe the sum of the various mass components integrated within the radius at which the dynamics are measured. These dynamical masses, in conjunction with independent measures of the mass of the stellar content from our ancillary data, were used to derive gas masses under the assumption that the relative contribution of dark matter in the internal regions of galaxies is low. The resultant estimated gas masses were then compared to the [CII] luminosity in these ALPINE galaxies to explore whether [CII] is indeed a reliable tracer of the molecular gas mass. If confirmed, this would open a new window at high redshift for molecular gas mass estimates, as the detection of both CO emission and thermal dust emission is considerably more difficult with ALMA at these redshifts, and the former requires uncertain assumptions about the spectral energy distribution of various CO transitions. For this sample, we found a statistically consistent agreement between the gas masses derived from dynamical masses and [CII] luminosities.

Encouraged by this agreement, we assumed the [CII]-derived gas masses to be reliable for all 44 ALPINE non-merger [CII]-detected galaxies and extend the gas mass estimates to this sample to explore the redshift evolution of the molecular gas depletion timescale and the fraction of gas to total baryonic mass for $z > 4.5$. The ALPINE galaxies showed depletion timescales as long as 4.8×10^8 yr at $z \sim 5$, corresponding to star formation efficiencies only twice as high as in present-day galaxies, and a flattening of the gas fraction at $z > 4$, reaching a mean value of 65% at $z \sim 5$. This behaviour of the gas fraction is fully in line with the redshift evolution of the average star formation rate per unit stellar mass at the same redshifts (Khusanova et al., 2020).

Conclusion

The ALPINE surveys have demonstrated the importance of millimeter observations to understanding the nature of normal star-forming galaxies at $z > 4$. This first [CII] sample at $z > 4$ that is statistically representative of normal star-forming galaxies at these redshifts has provided hints of the nature of the complex and dynamic life of such galaxies and raises important new questions. The ALPINE survey will have an important legacy value for both observers and modellers and its products are publicly available to the global astronomical community[1, 2].

Acknowledgements

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This article is dedicated to the memory of Olivier Le Fèvre.

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Links

[1] The data products and catalogues will be released on this website: https://cesam.lam.fr/a2c2s/

[2] Outreach material is provided on this website: http://alpine.ipac.caltech.edu

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A Rare Pair of Eclipsing Brown Dwarfs Identified by the SPECULOOS Telescopes

Amaury H. M. J. Triaud[1]
Adam J. Burgasser[2]
Artem Burdanov[3]
Vedad Kunovac Hodžić[1]
Roi Alonso[4]
Daniella Bardalez Gagliuffi[5]
Laetitia Delrez[6]
Brice-Olivier Demory[7]
Julien de Wit[8]
Elsa Ducrot[3]
Frederic V. Hessman[9]
Tim-Oliver Husser[9]
Emmanuël Jehin[10]
Peter P. Pedersen[6]
Didier Queloz[6]
James McCormac[11]
Catriona Murray[6]
Daniel Sebastian[3]
Samantha Thompson[6]
Valérie Van Grootel[10]
Michaël Gillon[3]

[1] School of Physics & Astronomy, University of Birmingham, UK
[2] Center for Astrophysics and Space Sciences, University of California, San Diego, La Jolla, USA
[3] Astrobiology Research Unit, Université de Liège, Belgium
[4] Instituto de Astrofísica de Canarias, La Laguna, Spain
[5] Department of Astrophysics, American Museum of Natural History, New York, USA
[6] Cavendish Laboratory, Cambridge, UK
[7] University of Bern, Center for Space and Habitability, Switzerland
[8] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, USA
[9] Institut für Astrophysik, University of Göttingen, Germany
[10] Space Sciences, Technologies and Astrophysics Research (STAR) Institute, Université de Liège, Belgium
[11] Department of Physics, University of Warwick, Coventry, UK

Brown dwarfs — stellar objects unable to sustain hydrogen fusion in their cores because of their low masses — continuously cool over their lifetimes. Evolution models have been created to reproduce this behaviour, and to allow mass and age determination using their luminosity, temperatures, spectral types and other parameters. However, these models have not yet been fully validated or calibrated with observations. During a commissioning run of the SPECULOOS telescopes, we serendipitously discovered a rare double-line eclipsing binary, a member of the 45 Myr-old moving group Argus. This discovery permitted us to determine the masses, radii and ages of the brown dwarfs, and with their luminosities make a comparison to evolution models. The models reproduce these measurements remarkably well, although a measured offset in luminosity could result in systematic underestimation of brown dwarf masses by 20 to 30%. Calibrating these models is necessary as they are also used to infer the masses of young, directly imaged exoplanets such as those found at the VLT.

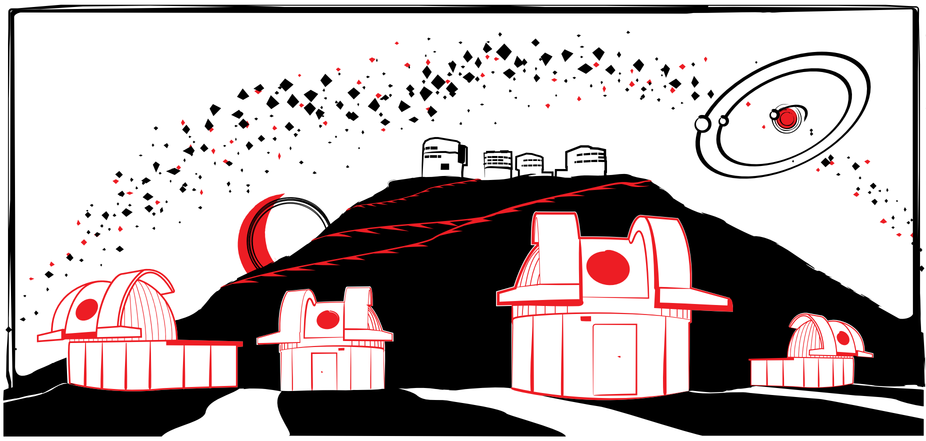
Introduction

Several methods are used to measure the radii of celestial objects. Most generally, astronomers combine parallax, bolometric luminosity and effective temperature and use the Boltzmann law ($L = 4\pi R^2\sigma T^4$) to determine a radius. For sufficiently bright and nearby systems, or for bright, large stars, interferometry can be used to directly measure stellar discs (for example, Demory et al., 2009). Alternatively, one can use the blocking of starlight during a lunar occultation or an eclipsing binary system to measure size (for example, Torres et al., 2010). Thanks to parallax measurements, radii for millions of stars are already determined from luminosities and temperatures. With Gaia, billions more are being inferred. However, masses cannot be measured for the vast majority of these stars.

The best-established method of measuring the mass of celestial objects is through the gravitational pull of one object on another. This is commonly achieved in co-orbital systems, such as a pair of stars or a satellite orbiting a planet. Using a time series of spectroscopic measurements, one can obtain the line-of-sight velocity along the orbit and obtain a lower limit on mass. If only one star is detected, the mass of its companion can only be inferred by assuming a mass for the detected object. These are called single-line binaries, and include exoplanets detected by the radial-velocity method. If the velocities for both stars are detected, i.e., in double-line binaries, we can directly measure the mass ratio of the pair. In either case, we need to know the orbital inclination of the system with respect to the plane of the sky to obtain the true masses of the objects.

Eclipsing double-line binaries circumvent this restriction by allowing one to measure the inclination angle (even when not entirely edge-on) and hence the true masses. These systems have been used to calibrate stellar models and study the physical properties of stars (for example, Torres et al., 2010). The eclipses themselves permit the measurement of

Figure 1. Illustration of the four SPECULOOS telescopes constructed at Paranal, showing the VLT in the background, a rising moon and a planetary system symbolising our aspirations. The Milky Way arches over the scene, resembling a photometric time series within which there is a planetary transit.



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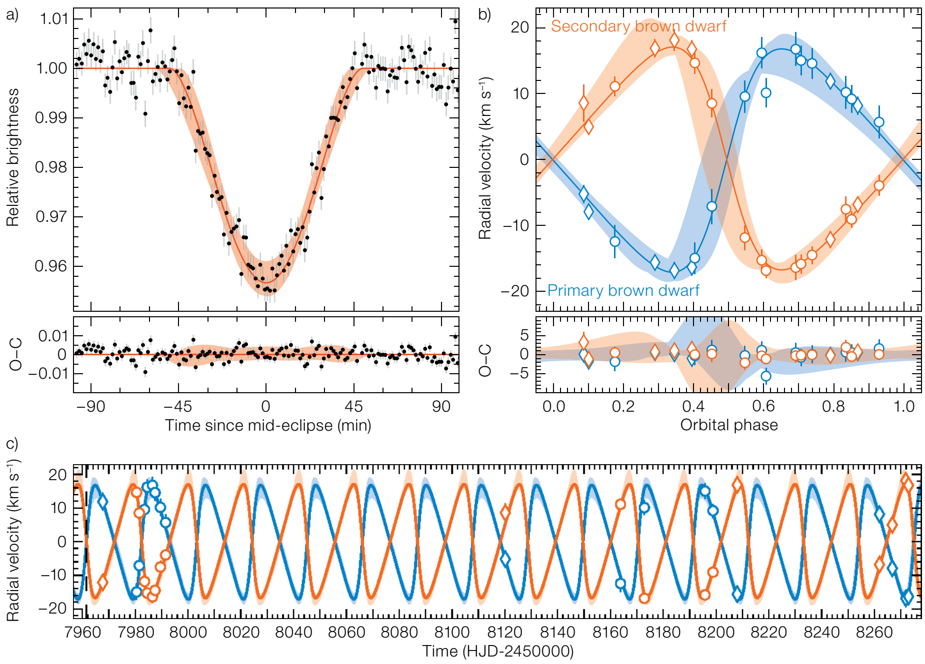

Figure 2. Data confirming the detection of a brown dwarf double-line eclipsing binary (Triaud et al., 2020). (a) Photometric time series obtained during a commissioning run of the SPECULOOS facility at Paranal, showing a 4% deep grazing eclipse. (b) Radial-velocities as a function of orbital phase. Dots represent UVES measurements, while diamonds were obtained with NIRSPEC. (c) Radial velocities as in (b), but as a function of time. The dashed line at day 7961 shows when the eclipse of a) was observed. In all plots, the shaded areas depict the 2-sigma uncertainty about the best fit model. Figure from Triaud et al. (2020).

the relative luminosities of the binary components, a function of their sizes and temperatures. Since temperatures can usually be determined from the same spectra that we collected to measure mass, we can uniquely solve for the masses and radii of the pair.

Age is also a fundamental parameter, particularly for brown dwarfs, as these sources constantly cool and never reach a main sequence (Kumar, 1962; Hayashi & Nakano, 1963; Baraffe et al., 2003). At sufficiently old ages, brown dwarfs can become too cold and dark to be detected; the coldest known brown dwarf to date has a temperature of 250 K (Luhman, 2014). Age cannot generally be determined directly for stars and is instead inferred for Sun-like stars from proxies such as rotation, magnetic activity or kinematics. For brown dwarfs, age can be inferred from evolution models if mass, radius and luminosity are simultaneously known, but such cases are rare. Thankfully, ages for brown dwarfs can be inferred if they are associated and coeval with other stars in wide binaries or stellar clusters and associations. However, it is rare to also be in a position to measure the masses or radii of these brown dwarfs as we do here.

The SPECULOOS project

The goal of the Search for habitable Planets EClipsing ULtra-cOOl Stars project (SPECULOOS[1]) is to look for systems similar to the seven temperate rocky worlds of TRAPPIST-1[2] (Gillon et al., 2017), which was found during a pilot survey with the TRAnsiting Planets and PlanetesImals Small Telescope at Cerro La Silla (TRAPPIST-South). SPECULOOS is based on a constellation of six robotic telescopes. Four of the telescopes are located at ESO's Paranal Observatory, one on el Teide in Tenerife (Spain), and another at San Pedro Mártir in Lower California (Mexico). The telescopes were constructed by the Universities of Birmingham, Cambridge and Bern, the Instituto de Astrofísica de Canarias (IAC) and Massachusetts Institute of Technology (MIT), led by the University of Liège. The collaboration also involves researchers from other institutions, and some observations are obtained with the TRAPPIST telescopes at La Silla and Oukaïmeden (Morocco).

The telescopes all have 1-m-diameter mirrors and deep-depleted back-illuminated CCDs that are able to observe efficiently in the near-infrared. The performance of the telescopes and our main research activities were described in a previous Messenger (Jehin et al., 2018). The four telescopes at Paranal, named after moons of Jupiter (Io, Europa, Ganymede and Callisto) officially initiated their survey for transiting planets in January 2019.

Observational campaign

During the commissioning of Europa, and to test the performance of the telescope and its camera, a brown dwarf called 2MASSW J1510478-281817 (hereafter 2M1510), with an M8 spectral type, was monitored for several nights. This source was chosen for its brightness and location on the sky, reaching the zenith and crossing the meridian near the middle of the night. On the second night of observations, an eclipse with 4% depth was detected with a shape similar to those produced by grazing eclipsing binaries (Figure 2a). Observations obtained during subsequent nights showed the source was photometrically stable, implying that the signal was likely real.

A search of the scientific literature revealed a crucial piece of information. 2M1510A has a known common proper-motion companion (2M1510B) located seven arcseconds away (about 250 au), which too has an M8 spectral type. Interestingly, the companion was noted to be fainter by a factor of two by Gizis (2002) who wrote that "[2M1510A] might be an equal luminosity double," suggesting the presence of a binary system.

Separately, Gagné et al. (2015) proposed that 2M1510 is a member of the young moving group Argus, which contains 35 other stars with an age of 45 ± 5 Myr, a fact that we were able to confirm with our subsequent radial velocity measurements.

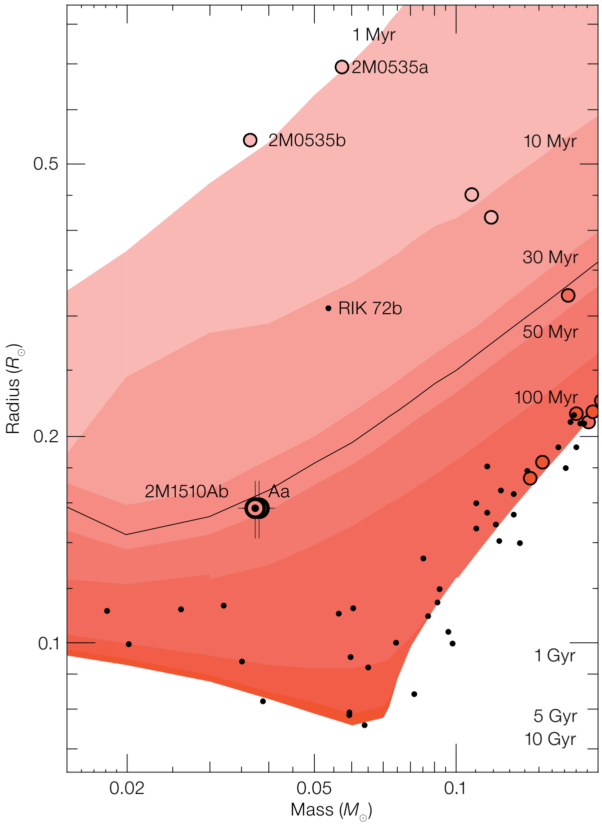

Figure 3. Mass-radius diagram displaying all known mass and radius measurements within this parameter space. Single-line binaries and measurements obtained from interferometry are shown as black dots, while double-line eclipsing binaries are represented as open circles. Three brown dwarf systems are labelled by name, including 2M1510Aab — the system we discovered. The coloured areas represent the Exeter/Lyon evolution models (Baraffe et al., 2003, 2015), with changes in tone corresponding to ages labelled in the diagram. The 40 Myr isochrone is highlighted in black and 2M1510Aa and 2M1510Ab fall between the 40 and 50 Myr isochrones, independently consistent with the age of the Argus moving group. Figure from Triaud et al. (2020).

To verify that 2M1510A was a binary, we first obtained a single spectrum using the near-infrared spectrograph NIRSPEC on Keck II, which showed 2M1510A to be a double-line binary. We then applied for an ESO Director's Discretionary Time (DDT) programme to use the Ultraviolet and Visual Echelle Spectrograph (UVES) on the VLT to monitor the motion of the binary components. Less than three weeks after the eclipse, we were able to determine the orbital period and relative luminosity of the system. The UVES and NIRSPEC data combined revealed a near equal-mass binary on an eccentric 21-day orbit with a timing consistent with the eclipse we had observed (Figures 2b & 2c). We later refined the orbital parameters with further observations with NIRSPEC and UVES. We also monitored the source repeatedly to search for a second eclipse, which eluded us until a partial event was obtained using the Las Cumbres Observatory Global Telescope (LCOGT) 1-m telescope at Siding Springs (Australia), nearly two years after the first event.

Our results

From the radial velocities of the components obtained with UVES and NIRSPEC, and the photometry from SPECULOOS, we found that the two brown dwarfs have almost equal masses of 40 Jupiter masses (within uncertainties). Unfortunately, the current configuration means that only one eclipse is visible, near periastron, when the more massive component (2M1510Aa) of the pair partially covers the less massive component (2M1510Ab). At apastron, their discs do not overlap. This makes it harder to measure radii, since we can only measure the sum of the two radii from the shape of a single eclipse. Fortunately, since both objects have near equal mass and temperature, we can safely assume their radii are similar too, which we measure to be 1.6 times the radius of Jupiter.

By placing the masses and radii on a mass-radius diagram (Figure 3), and comparing them with evolution models from the Exeter/Lyon group (Baraffe et al., 2003, 2015), we find that the system overlaps almost perfectly with a 40 Myr isochrone, close to the age of the Argus Association, validating those models as well as the physics within them at an "evolved" age for the first time.

Interestingly, we do not find as good a match for the luminosities of the system. The Exeter/Lyon models predict absolute magnitudes for 40 Myr-old objects which, correcting for distance and the binary nature of the system, do not match the apparent magnitudes of the components as measured by 2MASS.

Conclusions

Usually, the masses of young brown dwarfs in young associations or co-moving groups are estimated using evolution models, based on their absolute magnitudes, effective temperatures and the age of the group. Following this procedure, we would find a mass for 2M1510A that is 20–30% lower than dynamically measured. The reason for this discrepancy may be linked to the treatment of various opacities in brown dwarf atmospheres, which are sufficiently cool that condensates can form in abundance. Our results suggest that the physics of the evolution models is correct to first order, but that further refinements, such as their atmospheric properties, may be required.

Similar models are routinely used to infer the masses of directly imaged exoplanets, such as those detected with NACO and SPHERE on the VLT. Our work suggests that those mass determinations may have to be revised in the future as evolution models are calibrated with systems like 2M1510A.

Systems with mass, radius, age and luminosity measurements are extremely valuable for calibrating evolution models, which can then be applied to objects that are single, or for which age is hard to determine. In the case of brown dwarfs, however, evolution models lack sufficient calibration. The system we identified is only the second double-line eclipsing brown dwarf system discovered to date. Several single-line binary systems containing brown dwarfs eclipsing main sequence stars have been identified by transiting exoplanet surveys (for example, Hodžić et al., 2019), but characterisation of the brown dwarf depends on the correct characterisation of the primary star. The only other double-line eclipsing brown dwarf known was detected in 2006 (Stassun et al., 2006). This object, called 2M0535, is located in the 1 Myr-old Orion cluster, and its physical properties diverge from models, likely due to the effects of magnetic activity or ongoing accretion. The prevailing thinking is that, at these young ages, models cannot encompass the stochasticity of star formation and the variety of physical processes taking place. At later times the physical properties of these objects should converge with theoretical tracks.

Acknowledgements

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This research has made use of PyRAF which is a product of the Space Telescope Science Institute, which is operated by AURA for NASA. PyRAF uses IRAF, which is distributed by NOAO, which is operated by AURA, under cooperative agreement with the NSF. We used: the SIMBAD database, operated at CDS, Strasbourg, France; NASA's Astrophysics Data System Bibliographic Services; the M, L, T, and Y dwarf compendium; and the SpeX Prism Libraries. The authors recognise and acknowledge the very significant cultural role and reverence that the summit of Maunakea has within the indigenous Hawaiian community. We are most fortunate and grateful to have had the opportunity to conduct observations from this mountain. This research also made use of several Python packages including Astropy[3], a community-developed core Python package for Astronomy as well as the open-source Python packages NUMPY[4], SCIPY[5] and MATPLOTLIB[6].

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Triaud, A. H. M. J. et al. 2020, Nature Astronomy, DOI 10.1038/s41550-020-1018-2

Links

[1] SPECULOOS website: www.speculoos.earth
[2] TRAPPIST-1 website: www.trappist.one
[3] Astropy: www.astropy.org
[4] NUMPY: www.numpy.org
[5] SCIPY: www.scipy.org
[6] MATPLOTLIB: www.matplotlib.org

ESO/H. Zodet

Two of the SPECULOOS telescopes searching for exoplanets around nearby stars and brown dwarfs. The Milky Way stretches over them across the left hand corner of the image.

Above: Screenshot taken at the end of the welcome workshop for the ESO Summer Programme 2020 students. The camera was turned on by the five students and two of the organisers, Rosita Kokotanekova and Carlo Manara. Other attendees and organisers can be seen by their initials in the bottom bar.

Below: Screenshot of one of a series of ESO Cosmic Duologues. This duologue was focussed on dust at high-z. All of the ESO Cosmic Duologues are available to watch on YouTube.

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Report on the ESO/ALMA Conference

ALMA 2019: Science Results and Cross-Facility Synergies

held in Cagliari, Italy, 14–18 October 2019

Ciska Kemper[1]

[1] ESO

The Atacama Large Millimeter/submillimeter Array (ALMA) is the largest and most sensitive millimetre/submillimetre array on the planet, with the highest spatial resolution. Since it began operating, ALMA has routinely been at the forefront of science in this wavelength regime, delivering ground-breaking discoveries. The ALMA 2019 science conference was organised as one of a series of meetings held at regular intervals for the worldwide ALMA community, the previous one being held in Indian Wells, USA in 2016. At the start of Cycle 7 of observations, the ALMA 2019 conference provided an opportunity for the community to reflect on the multitude of scientific results from the facility, with special emphasis on the results from the first rounds of ALMA Large Programmes, the long baselines and high-frequency capabilities, the new solar and very long baseline interferometry (VLBI) modes, as well as the synergy between ALMA and other observatories.

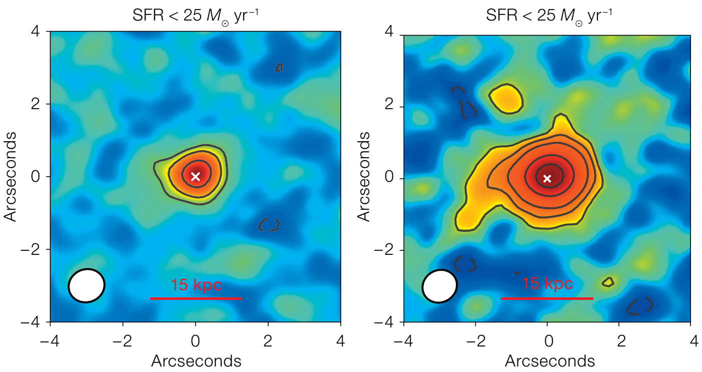


Figure 1. Extended [CII] emission observed in the circumgalactic medium of stacked ALPINE galaxies, from the talk by Michele Ginolfi.

Motivations

The ALMA observatory on the Chajnantor plateau in the Atacama desert in Chile is the largest and most sensitive submillimetre and millimetre array available. Its 66 antennas provide sub-arcsecond resolution in this wavelength regime. With eight receivers currently operating and a further two under construction, the frequency range from 35 to 950 GHz will ultimately be accessible with high spectral resolution. In addition, polarisation and VLBI measurements are being conducted with ALMA. It is a highly successful observatory, as evidenced by its ever-growing worldwide user base and more than 1600 publications after seven years of operation. ALMA is an important facility across a wide range of science topics, including cosmology, galaxies in the distant universe, nearby galaxies, the Galactic centre, interstellar matter and star formation, astrochemistry, circumstellar discs, exoplanets, the Solar System, stellar evolution and the Sun. The ALMA project is a joint effort by three regions: Europe (ESO), North America (USA, Canada and Taiwan) and East Asia (Japan, Taiwan and Korea), and in addition to topical and regional meetings, the worldwide ALMA community meets every 2–3 years for a truly global conference. Earlier examples include the ALMA science meetings in Puerto Varas (Chile, 2012), Tokyo (Japan, 2014) and Indian Wells (USA, 2016). In October 2019, it was Europe's turn to organise the community-wide science meeting in a joint effort between ESO and INAF – Cagliari in Italy.

A major theme of the meeting was the focus on Large Programmes and their initial results. Large Programmes (> 50 hours of observing time) were introduced in Cycle 4 (2016–2017), which saw the approval of two of them. A further four Large Programmes were approved in each of Cycle 5 and Cycle 6. In order to showcase the results from these Large Programmes we invited a key collaborator from each of the Cycle 4 and Cycle 5 Large Programmes to present their results. Since Large Programmes can run up to two cycles, observations for Cycle 6 Large Programmes were not yet completed at the time of the conference. Nevertheless, some initial results from the Cycle 6 programmes were presented in the contributed talks. Other main themes included synergies with other facilities which were taken into account when creating the science programme, and the priorities from the ALMA 2030 Development roadmap which were a major topic, in particular in the poster presentations.

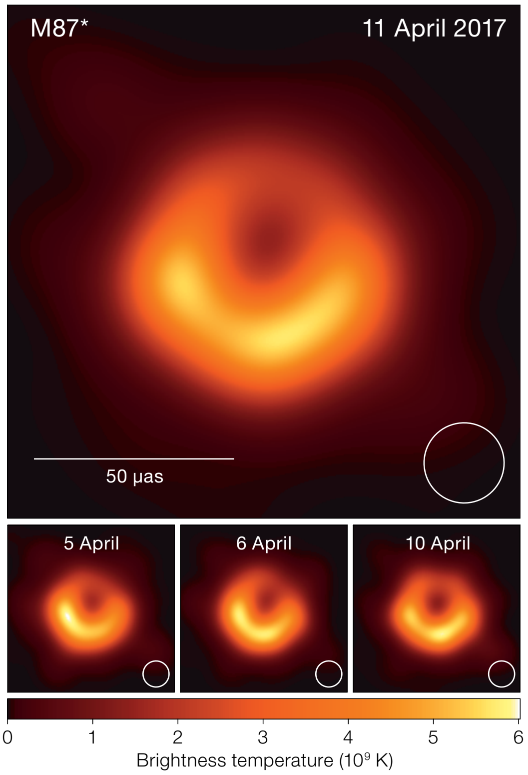
The programme was organised according to the five science categories of the ALMA proposal submission process, with four invited talks in each of the science categories I through IV, and two invited talks in science category V, which only receives about half the observing proposals compared to each of the other four science categories. Broadly, the five science categories are:

i. Cosmology and the high-redshift Universe;
ii. Galaxies and galactic nuclei;
iii. Interstellar medium (ISM), star formation and astrochemistry;
iv. Circumstellar discs, exoplanets and the Solar System;
v. Stellar evolution and the Sun.

The programme also included an observatory talk to open the conference and a conference summary, yielding a total of 20 invited talks covering a diverse range of topics. The science categories were divided over sessions consisting of two or three blocks of talks each and we alternated between topics during the week in order to enhance interaction between the categories. Most presenters have made their slides available on Zenodo[1], and the majority of the poster presentations can also be found on Zenodo at the same URL.

Summaries of talks and highlights from sessions

Session I on Cosmology and the high-redshift Universe was spread over Monday, Wednesday and Friday and included both the opening and closing sessions of the conference. Three Large Programmes were discussed in the context of this session. Roberto Decarli gave a presentation on the ALMA Spectroscopic Survey in the Hubble Ultra Deep Field (ASPECS) which is a spectroscopic survey in Bands 3 and 6 (3 and 1.3 mm) of a significant



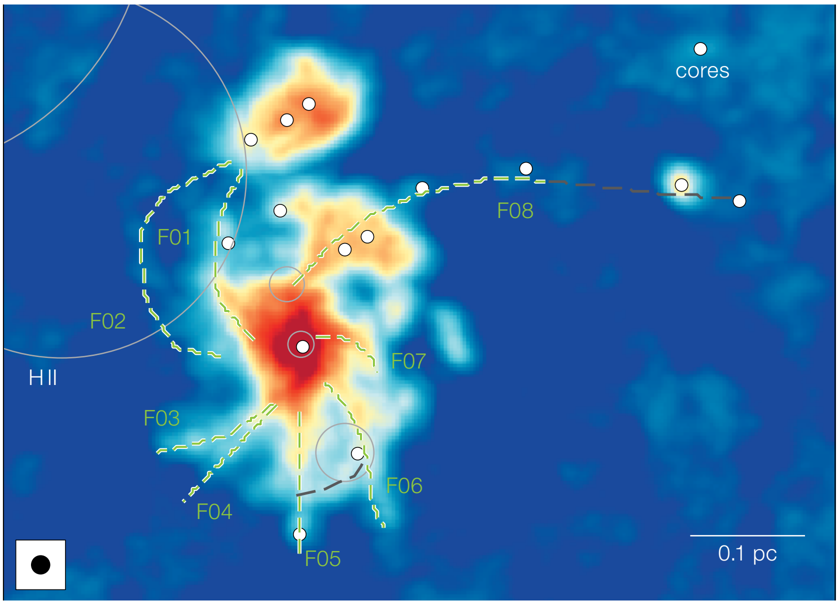


Figure 2. (Left) The iconic image of the shadow of the supermassive black hole in the centre of M87 as detected by the Event Horizon Telescope collaboration, and presented by Shep Doeleman.

Figure 3. (Above) Converging filaments leading towards the formation of the super star cluster Sgr B2. From the talk by Alvaro Sanchez-Monge.

part of the Hubble Ultra Deep Field, in order to follow the evolution with redshift of the interstellar gas and dust reservoirs of galaxies. The first results show that the gas masses do indeed follow the star formation history of the Universe and the survey also boasts the deepest 1.3-mm continuum map ever. From Michele Ginolfi we heard about the ALMA Large Programme to INvestigate [CII] at Early times (ALPINE), which uses [CII] emission lines and continuum measurements to study star formation and galactic evolution at high redshift. In addition to analysing the sample, it has been possible to stack all galaxies and study the extent of [CII] emission in the circumgalactic medium, a result also highlighted by Seiji Fujimoto in a contributed talk. The presence of carbon demonstrates that galaxies are able to enrich their circumgalactic medium with the products of nucleosynthesis early in the history of the Universe — at redshifts $5 < z < 7$. In another contributed talk, Kotaro Kohno reported on preliminary results from a Cycle 6 Large Programme, the ALMA lensing cluster survey. Further talks in Session I also covered topics related to cluster formation — see, for example, the contributions by Axel Weiss — and the Sunyaev-Zeldovich effect (talks by Luca Di Mascolo and Tony Mroczkowski). Loretta Dunne presented a calibration of atomic and molecular gas and dust mass determinations at different redshifts.

Session II, dealing with galaxies and galactic nuclei, was spread over subsessions on Tuesday, Wednesday and Thursday. This session featured the spectacular results on the imaging of the black hole shadow in M87 by the Event Horizon Telescope. In an invited talk, Shep Doeleman reported on the observations and detailed data analysis behind the discovery. In a related contributed talk, Lindy Blackburn discussed VLBI observations at 3 mm of the immediate surroundings of Sgr A*, and the modelling required to interpret the observations. In addition, two Large Programmes were discussed. Sergio Martín reported on the ALMA Comprehensive High-resolution Extragalactic Molecular Inventory (ALCHEMI), which is doing a spectral line survey of NGC 253 in five different bands. The PHANGS Large Programme, which aims to study resolved star formation in ~ 50 nearby galaxies, was presented by Eva Schinnerer. She showed the participants stunning maps of the distribution of molecular gas through, for example, CO(2-1) emission in spiral galaxies, revealing a distribution distinctly different from that of the ionised gas tracing the star formation. The ratio of ionised and molecular gas emission also varies greatly between galaxies. Studies of CO clouds in Local Group galaxies were presented by Atsushi Nishimura for M33, and by Katie Jameson for the Small Magellanic Cloud, the latter being a full survey of the bar of the SMC with the Atacama Compact Array (ACA). Quasars and active galactic nuclei were the topics of several of the other talks in this session, with special attention going to the dynamics of the torus and outflows, and the chemistry in these environments.

Session III covered the interstellar medium, star formation and astrochemistry in subsessions spread over the first three days of the conference. The highlights of this session include the discussion of the Large Programme “ALMA transforms our view of the origin of stellar masses” (ALMA-IMF) by Fabien Louvet, who showed results determining the initial cloud mass function in 15 massive star-forming regions within 6 kpc traced in different molecular lines, also revealing

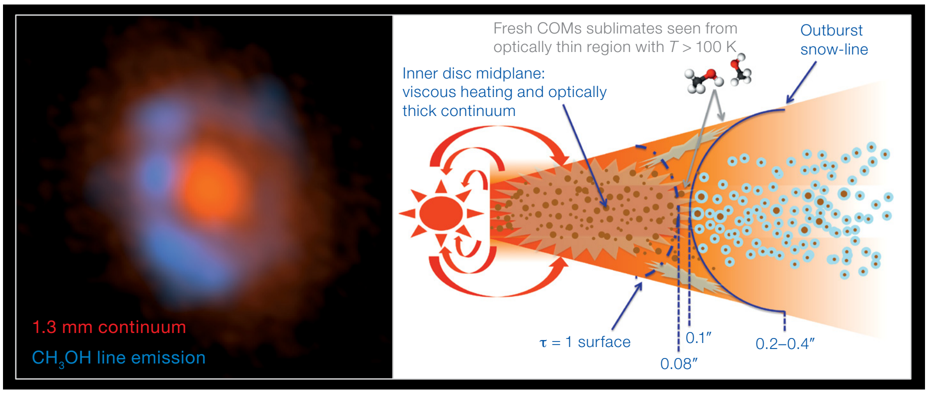


Figure 4. The detection of a ring of methanol around V883 Ori representing the first detection of complex organic molecules associated with planet formation. From the talk by Jeong-Eun Lee.

filaments and outflows in these regions. Spectacular images showing converging filaments leading to the formation of the super star cluster Sgr B2 were presented by Alvaro Sanchez-Monge. This session also featured several talks on ALMA polarisation measurements tracing magnetic fields in the ISM and star-forming regions, as well as other astrophysical environments. Chat Hull delivered a talk on enhanced polarisation in the outflow cavities of young stars, while Tanmoy Laskar discussed the detection of polarised emission from the reverse shock associated with a gamma-ray burst, revealing a very low polarisation fraction of less than 1%.

Session IV on circumstellar discs, exoplanets and the Solar System was spread over two days. Sean Andrews presented an overview of the Disk Substructures at High Angular Resolution Project (DSHARP) Large Programme on small-scale structure in a sample of 18 protoplanetary discs, showing a range of discs, rings and asymmetries in continuum emission, some of which could be assigned to the interaction with newly formed planets. Several talks, including those by Jeong-Eun Lee and Ilse Cleeves addressed the chemical evolution of planet-forming discs. Cleeves modelled the effect of X-ray flaring by the host star on the circumstellar disc in comparison with observations, while Lee follows the formation of complex organic molecules (COMs), and their “snow lines”. The topic of molecular snow lines was also addressed by Chunhua Qi in a contributed talk, who imaged the distribution of molecules susceptible to freeze-out, and secondary molecules able to trace this freeze-out. From Anna Miotello, we heard about the correlation and calibration between dust masses and molecular gas masses derived for protoplanetary discs.

Session V on stellar evolution and the Sun was the shortest session and was naturally split into a session on the Sun on Monday and a session on evolved stars on Thursday. Progress on solar astronomy with ALMA was reported by Sven Wedemeyer, Dale Gary and Stephen White, demonstrating the complementary contributions from ALMA to other facilities to studying the dynamic structure of the Sun at timescales shorter than 1 second. Thanks to its broad frequency coverage, ALMA can be used to probe the solar chromosphere at different depths. The session on evolved stars contained a few more talks on a range of topics. Leen Decin presented the initial progress of the Cycle 6 Large Programme ALMA Tracing the Origins of Molecular In dUst-forming oxygen-rich M-type stars (ATOMIUM), while Daniel Tafoya observed strongly collimated outflows in some evolved stars.

Owing to an overwhelming response to the poster session, posters were displayed in two sessions, with a change-over in the middle of the week. The poster sessions were very well attended. Four posters were highlighted by the poster prize committee, and their presenters, Philipp Weber, Sandra Treviño-Morales, Aleksandra Hamanowicz and Atefeh Aghababaei, were each given the opportunity to deliver a short talk on the same topic on the final day of the conference.

Main conclusions & ways forward

Looking back, it is safe to conclude that the conference was successful in bringing together the scientific community using ALMA, and in presenting an overview of the science currently being done with the telescope. In particular, impressive results from the first two cycles of

Figure 5. Simultaneous imaging of the same part of the Sun at different wavelengths using different facilities, the first image on the second row being an ALMA Band 6 image. From Sven Wedemeyer’s talk.

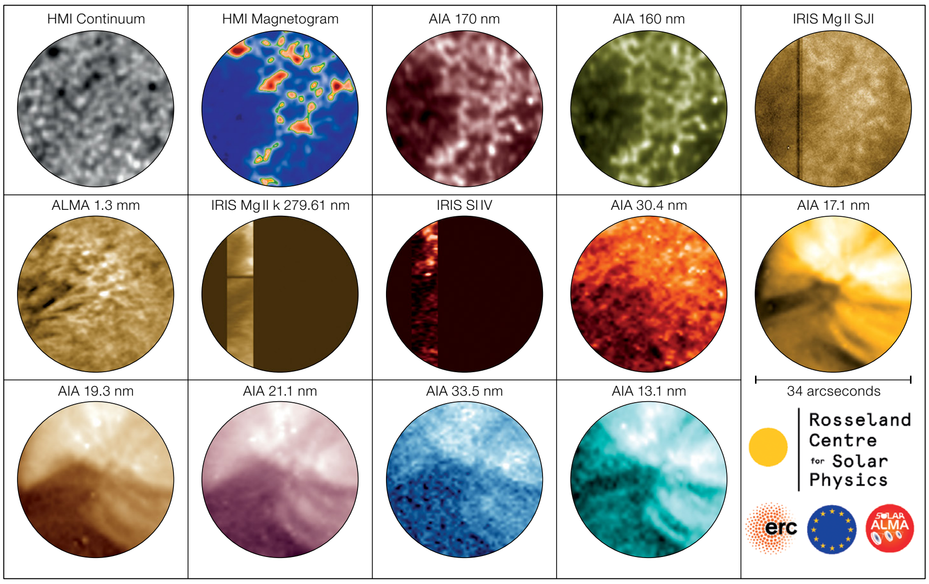


Figure 6. A poster made from a group photo of the participants.

Large Programmes were presented, as well as the detailed story behind the already famous image of the shadow of the black hole at the centre of M87. Specialised observing modes, such as polarisation, solar observations and VLBI, were well represented in the oral and poster presentations, along with the more standard line and continuum observations tracing interstellar and circumstellar gas and dust, in both the nearby and distant Universe. There is clearly a need for this kind of global ALMA meeting, and the consensus is that a next one should be organised in about 2022. Perhaps one of the key points of that meeting could be the synergy with other facilities as this aspect remained somewhat underexamined in the ALMA 2019 conference.

Demographics

The Science Organising Committee (SOC) sought fair representation from the community. We had four invited speakers in science categories I through IV listed above, and two invited speakers in science category V, which represents the proportionally smaller size of the scientific community, as evidenced by the observing proposal pressure in this category. The PIs, or designated representatives, of all of the six Cycle 4 and 5 Large Programmes were amongst the 18 invited speakers, and the remaining 12 spots were filled by science area, where we aimed to achieve gender and regional balance. In this case, the term regional refers to the three ALMA executives or regions (Europe, North America and East Asia). Two more invited talk slots were reserved for an overview of the status of the observatory by the ALMA director, and the conference summary.

The SOC selected the contributed talks based on scientific merit, although in cases with equal scoring of multiple abstracts for a single remaining slot, gender and regional balance considerations were taken into account. In total, exactly half of the invited speakers were women, and approximately one third of the contributed talks were delivered by women.

The conference proved to be very popular during the registration phase, and the venue limit of 250 participants was exceeded overnight on the day of the abstract submission deadline for contributed talks. We thus had to close registration, even though the originally planned registration deadline was later, and were forced to waitlist about 70 registrants. The waitlisting was done after the contributed talk selection and was primarily based on the scientific merit of the submitted abstract. As a result of cancellations in the weeks following the announcements of the contributed talk schedule, the waitlist fortunately disappeared completely and ultimately everyone who had wanted to attend the conference and had been registered by the abstract submission deadline was able to attend.

The conference was attended by 216 participants. An additional 17 participants from Japan were not able to make it as a typhoon hit the Tokyo metropolition area on the weekend before the start of the conference, which prevented many participants departing for Italy. Of the participants, 29 were students at the time of the conference. We encouraged the conference attendees to participate in an anonymous demographic survey and received 182 responses. Of these respondents, 55.5% (101) indicated they were male, 44.0% (80) female and 0.5% (1) of the respondents preferred not to say their gender. The geographical origin of the respondents, based on their current affiliation, was well distributed over the ALMA regions, with 45.1% (82) from Europe, 30.2% (55) from Asia, and 20.9% (38) from North America. A further 3.3% (6) were from South America, and 0.5% (1) was from Australia. None of the respondents was based in Africa.

Acknowledgements

The ALMA 2019 conference was jointly organised by ESO and the Osservatorio Astronomico di Cagliari (INAF) and was financially supported by INAF, RadioNet and ESO. The conference also hosted an itinerant “Inspiring Stars” exhibition from the IAU, in Italian.

Links

[1] Presentations and posters from meeting available via Zenodo: https://zenodo.org/communities/alma2019caligari

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Report on the ESO Summer School

La Silla Observing Summer School 2020

held at ESO La Silla, Chile, 3–14 February 2020

Emanuela Pompei[1]
Johanna Hartke[1]
Heidi Korhonen[1]
Chiara Mazzucchelli[1]
Camila Navarrete[1]
Anna F. Pala[1]
Luca Sbordone[1]
Linda Schmidtobreick[1]

[1] ESO

The La Silla Observing Summer School was originally conceived with the goal of providing hands-on training in the use of telescopes and astronomical instruments for senior masters and young doctoral students. The third La Silla Summer School ran over two weeks and was hosted by ESO's Office for Science and the La Silla Observatory. Twenty PhD and MSc students from several countries participated. They attended lectures on various observing modes and instrumentation but also on scientific presentations, time management, effective proposal writing, and career choices. For the hands-on part at the observatory, the students were supervised by seven ESO tutors. Four small research projects were offered, using three telescopes and four instruments. The students in each research group went through the full process of defining and discussing the observing strategies, conducting the observations, reducing and analysing the data and finally presenting the results to the scientific community at the ESO Vitacura offices. The next school is foreseen for the southern summer break of 2022.

Figure 1. The enthusiastic participants at the third La Silla Observing Summer School.

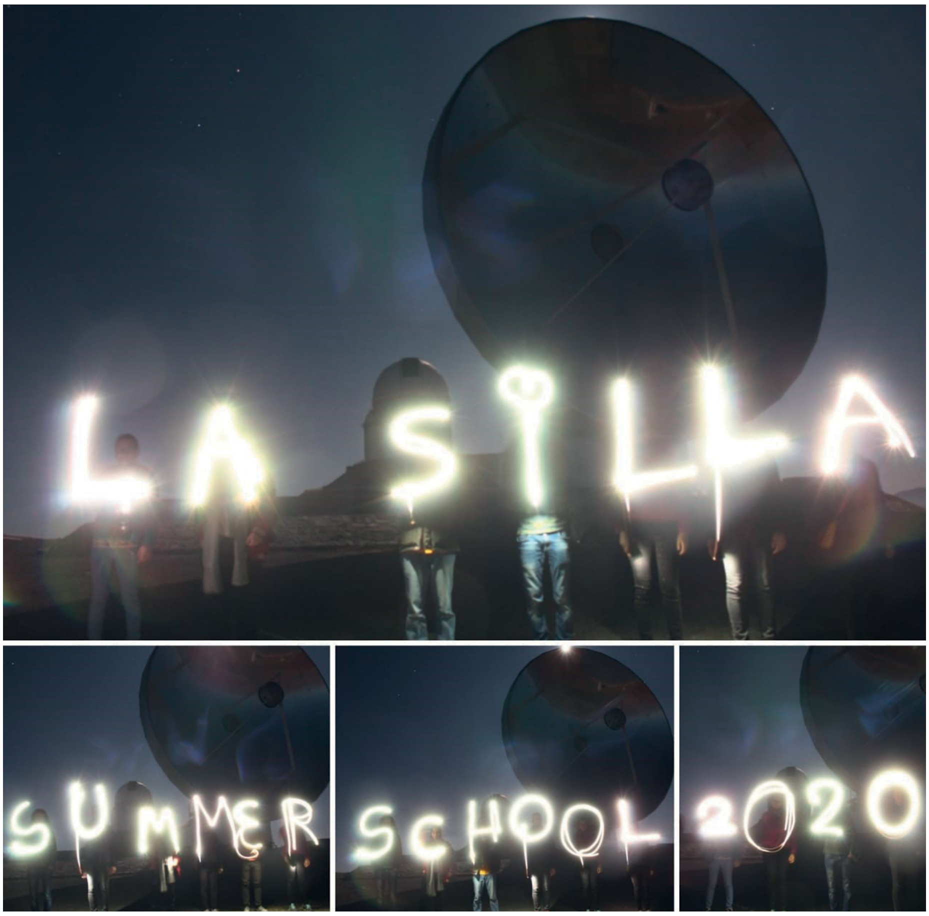

Figure 2. Happy students and tutors!

Introduction

Every two years, ESO hosts an observing school in La Silla during the summer break in the southern hemisphere, aimed at senior masters students and early doctorate students. The main goal of the school is to equip successful applicants with observational experience including, but not limited to, proposal preparation, observing strategy, data reduction, analysis and presentation of the results. This is becoming increasingly important, given the increasing use of remote observations, which denies many students the

Figure 3. Our time was divided between work and astro-tours.

possibility of having hands-on experience with large, modern observing facilities.

The previous versions of the school were organised primarily for students based in South America, given the relatively easy and cheap logistics which allowed us — with the generous contribution from OPTICON — to provide full support for accepted students, including travel costs. For this school, ESO provided paid lodging and transport. Students were housed in shared flats, which allowed the students to get to know each other in a relaxed environment.

During the first week, the students attended a series of lectures at the ESO premises in Vitacura. The students introduced themselves and shared their science interests and experience with their peers and the tutors. The participants then started to work in small groups on the specific science projects outlined below.

On Saturday 8 February, the students and tutors travelled to the La Silla Observatory; over the weekend they toured the site and familiarised themselves with the telescopes they were going to use. A special treat was a visit to the new BlackGEM[a] facility (see Figure 3). This time was also used to prepare observations, which began on the Danish 1.54-m telescope and the ESO New Technology Telescope (NTT) on 10 February, followed by the ESO 3.6-m telescope and the two telescopes above the following night. The instruments used for these observations were the Danish Faint Object Spectrograph and Camera (DFOSC; Andersen et al., 1995), ESO Faint Object Spectrograph and Camera v. 2 (EFOSC2; Buzzoni et al., 1984), Son of ISAAC instrument (SOFI; Moorwood, Cuby & Lidman, 1998), and High Accuracy Radial velocity Planet Searcher (HARPS; Mayor et al., 2003). The students returned to Santiago on 12 February, where they continued to analyse the data, discussed the results and prepared their presentations. On 14 February, the last day of the school, the students presented their results in Vitacura to an audience that included their colleagues, tutors, and ESO scientists. The successful conclusion of the school was then celebrated with a barbecue in the ESO grounds. The amount of work carried out over the two weeks was impressive and we were pleased to receive positive and useful feedback from the students.

The working groups

Four small research projects had been proposed by ESO staff astronomers and fellows, covering topics in stellar, Galactic and extragalactic astronomy. The students were divided into four groups: students with a background in extragalactic physics were assigned to stellar projects and vice versa, with the goal of encouraging them to explore outside their comfort zones and build strong collaborations. Care was also taken to evenly distribute expertise and seniority.

Characterising Nearby Galaxies with Optical Imaging

Tutor: Johanna Hartke
Students: Nicolas Rodriguez, Francesca Lucertini, Jon Joel Yael Galarza, Keila Y. Ertini, Paulina A. Miquelarena Hollger

The group observed nearby galaxies in isolation and in galaxy groups with the wide-field imager of the DFOSC at the Danish 1.54-m telescope[b]. The large field of view of the DFOSC, 13.7 × 13.7 arcminutes, and its pixel scale of 0.39 arcseconds, make it a perfect instrument for studying nearby galaxies. The aim of the project was to obtain photometry of these galaxies in different filters and to measure the

Figure 4. One of the highlights was a visit to one of the new BlackGEM telescopes.

Figure 5. The participants on one of the tours of the NTT.

Figure 6. The Hydra cluster with the brightest cluster galaxy NGC 3311 at its centre. The image was observed using the DFOSC at the Danish 1.54-m telescope.

galaxies’ surface brightness profiles and colour profiles as a function of radius. The students carried out isophote fitting of all the galaxies and identified different structural components, such as bulges, discs, and halos. As a by-product, they produced beautiful three-colour images of their targets, such as the Hydra cluster with the brightest cluster galaxy NGC 3311 at its centre (see Figure 6).

Characterising nearby and distant galaxies with optical imaging and spectroscopy

Tutor: Chiara Mazzucchelli
Students: Silvina Cardenas, Giada Casali, Iskra Georgieva, Alonso Luna, Raphael A. P. Oliveira

The group used EFOSC2 to collect long-slit spectroscopy of galaxies in the local Universe. Their aim was to characterise their nuclear emission (star formation vs active galactic nuclei), by detecting and measuring several emission lines, for example, Hα, [NII], Hβ, and [OIII]. In order to do this, they relied on well-known diagnostics from the literature used to analyse nebular emission, for example, BPT — Baldwin, Phillips & Terlevich — diagrams (see Baldwin, Phillips & Terlevich, 1981). In addition, the students determined the redshifts of the sources from several emission lines, and these appeared to be consistent with values in the literature. They also observed a nearby Seyfert galaxy, MRK0841, and obtained a measurement of its central black hole mass, after fitting its broad Hα and narrow [NII] and Hα emission lines. Finally, the students also collected *JHK* imaging with SOFI of the highest-redshift quasar known, J1342+0928 at z = 7.5. These points were added to the variability curve built from literature measurements and showed that the luminosity of the quasar did not vary significantly on a timescale of ~ 1.5 years.

Stellar Astrophysics in Omega Centauri

Tutors: Camila Navarrete and Luca Sbordone
Students: Juanita Antilen, Ana Ines Ennis, Aishwarya Girdhar, Ana Carolina Posses, Luis Carlos Vasconcelos

This group’s work consisted of identifying RR Lyrae pulsating variable stars in the globular cluster Omega Centauri and confirming them spectroscopically by detecting radial velocity variations, as well as analysing the chemical abundances of bright red giant branch (RGB) stars from two of the many stellar populations in the cluster. Gaia Data Release 2 (DR2, Gaia collaboration et al., 2018; Arenou et al., 2018) astrometry and photometry were used to clean up the Omega Cen colour-magnitude diagram (via proper-motion selection) and subsequently select stars for observation that were compatible with membership of the RR Lyrae population in the instability strip. Confirmed RR Lyrae members of the cluster were finally selected via a crossmatch with the catalogue of Navarrete et al. (2017).

Three of these were subsequently observed with EFOSC2 (Grism 14, spectral resolution R = 850) over two consecutive nights to confirm their pulsating nature. Their radial velocities were determined by cross-correlation. The radial velocity variations observed for all three targets were compatible with the expected pulsational phase. Using radial velocity lightcurve templates from the literature, the students derived the systemic velocity of the variables which was in good agreement with the mean radial velocity of the cluster, confirming their membership.

Two upper red giant branch (RGB) cluster member stars selected from the cleaned colour-magnitude diagram were also observed with HARPS to determine their chemical composition. The MyGIsFOS chemical analysis (Sbordone et al., 2014) revealed two very different objects, one in the lowermost ([Fe/H] = –1.98) and one in the upper ([Fe/H] = –1.35) part of the broad Omega Cen metallicity distribution, the latter object also being a rather chemically extreme second-generation star with strongly enhanced Na and Ba. Finally, the DFOSC at the Danish 1.5-m telescope was employed to obtain *B*, *V*, and *R* images of the entire Omega Cen cluster, from which a colour image of the object was derived.

In addition to the main science project, HARPS was also used to produce a very-high-resolution and high-S/N spectrum of Betelgeuse (Alpha Ori), which was undergoing the deepest photometric minimum ever observed at that time. The spectrum was immediately made public (Sbordone et al., 2020).

Spectroscopic identification of variable stars

Tutors: Ana F. Pala and Linda Schmidtobreick
Students: Avinash Chaturvedi, Lorenza Della Bruna, Eduardo Iani, Thais Pessi and Mattia Siressi

This science project aimed to provide the students with an understanding of stellar variability from both the spectroscopic and the photometric point of view. In particular, the group focused on the identification and study of cataclysmic variable (CV) candidates. These are compact interacting binaries hosting a white dwarf accreting from a main sequence star via an accretion disc. Candidates were selected because of their short variability timescales (of the order of minutes), allowing periodicity studies to be carried out and completed within the time window allocated for the observations.

From the catalogue presented in Pala et al. (2020), the students selected a total of 12 CV candidates for which they obtained identification spectra.

The ten faintest targets were observed with EFOSC2. From these spectra, the students confirmed that these systems are genuine CVs and classified them as low-, intermediate- and high-mass accreting systems (i.e., WZ Sge, SU UMa and U Gem CV sub-types) according to their spectral appearance. Interestingly, the students identified the presence of three CVs with nuclear evolved donors, which are the descendants of super-soft X-ray sources and are among the most promising supernova Ia progenitors in the single-degenerate scenario (Di Stefano, 2010).

The remaining two brightest targets, CoRoT 110741479 and V1129 Cen, were observed with HARPS and SOFI. Their spectra revealed that these systems are not CVs. In the case of CoRoT 110741479, the HARPS spectrum resembles that of an FU Ori-type young star, but more detailed studies are required in order to confirm this classification.

The SOFI spectrum of V1129 Cen acquired by the students represents the first near-infrared observation of this system and it was found to be dominated by a red star. Additional phase-resolved observations were carried out with HARPS. The detected radial velocity variation confirmed the multiple nature of the system, which previous work by Bruch (2017) had suggested was either a β Lyrae star (i.e., a close multiple stellar system) or a triple system consisting of an F star and a CV.

Finally, the students obtained time-resolved photometry with a two-minute cadence of the eclipsing CV RR Pic with DFOSC at the Danish 1.54-m Telescope. The observations delivered a 4-hour duration lightcurve of the system — thus covering the whole orbital period of 3.58 hours — and provided the students with an understanding of the relative orbital motions of the different components (the accretion disc, the donor star and the white dwarf) in a compact interacting binary.

Demographics

This year we decided to open the school to students worldwide and so did not offer travel support by default. We received approximately 100 applications evenly distributed between male and female applicants. Students applied from Chile, Argentina, Brazil, Venezuela, Ecuador, Colombia, France, Italy, Austria, Sweden, the United Kingdom, Iran, Ethiopia and Sudan. All applications were evaluated on an equal merit basis. Since travel support was unavoidably limited, a second selection was necessary to take into account whether the applicant was requesting travel support or not. The final selection resulted in 12 female and 8 male students, evenly distributed between senior masters and young doctorate students.

Acknowledgements

We wish to thank the Astronomical Institute, Czech Academy of Sciences, Ondrejov, Czech Republic for conceding two nights on the Danish 1.54-m telescope, the ESO Office for Science for their generous financial help and the La Silla Observatory for their kind hospitality and financial help.

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Links

[1] https://www.eso.org/sci/meetings/2020/lasilla_school2020.html

Notes

[a] BlackGEM is a wide-field array of optical telescopes, jointly developed by Radboud University, the Netherlands Research School for Astronomy (NOVA), and the KU Leuven. Its scientific goals are to detect and characterise optical counterparts to gravitational wave detections.

[b] The Danish 1.54-m telescope saw first light in 1978 and is used today in a collaboration between the University of Copenhagen in Denmark and the Astronomical Institute of the Czech Academy of Sciences, Czech Republic. The telescope control system was upgraded in 2012 with funding from the Czech Academy of Sciences, making the Danish 1.54-m a reliable telescope that is very easy to use. The telescope can be fully controlled remotely and is often used from Europe by both the Danish and Czech teams. Currently the telescope has two photometric instruments: the Danish Faint Object Spectrograph and Camera (DFOSC) and the Lucky Imager. The DFOSC, which was used during this school, has a 2k deep-depletion E2V CCD that was installed in November 2018. It has a field of view of 13.7 × 13.7 arcminutes and a plate scale of 0.39 arcseconds per pixel, making it a perfect instrument for the study of extended objects. On the whole, the hands-on approach and excellent telescope control system make the Danish 1.54-m an ideal facility for teaching observations.

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Report on the ESO Workshop

ESOz-2020: The Build-up of Galaxies through Multiple Tracers and Facilities

held at University of Western Australia, Perth, Australia, 17–21 February 2020

Claudia del P. Lagos[1,2]
Aaron S. G. Robotham[1,2]
Carlos De Breuck[3]

[1] International Centre for Radio Astronomy Research, University of Western Australia, Perth, Australia
[2] ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D)
[3] ESO

We report on the second joint Australia–ESO conference, held in Perth, Australia, following the successful Sydney conference in 2019. The conference was supported by ESO, the Centre of Excellence ASTRO 3D, the International Centre for Radio Astronomy Research, Macquarie University, CSIRO Astronomy and Space Science (CASS), and the Galaxies Journal. The scientific organising committee (SOC) focused on a programme that highlighted the complementarity between ESO and Australian instruments and the science breakthroughs enabled by this combination. In terms of demographics, we followed the same strategies as the previous meeting to tackle unconscious bias, and this again resulted in a well-balanced programme in terms of gender, career stage and geography, proving its effectiveness. Given concerns about global warming and the COVID-19 pandemic, the local organising committee (LOC) allowed several talks to be delivered remotely, and we reflect on that experience here.

Motivation

We are obtaining the first major results from a huge variety of "pathfinder" facilities that are operating with entirely new types of survey instruments. These pathfinders share the common aim of untangling galaxy evolution physics, and so it is important that the first science results are communicated across various disciplines. This was the main purpose of this second Australia–ESO (aka ESOz[1]) conference together with encouraging the community to start having serious conversations about the future coordination of next-generation galaxy evolution surveys.

Truly panchromatic surveys such as the Cosmological Evolution Survey (COSMOS) and Galaxy And Mass Assembly (GAMA) have shown that by coordinating across disciplines, new areas of astrophysics are inevitably opened up. Both of these surveys attempted to measure almost all of the energy generated by stars and active galactic nuclei (AGN) and reprocessed by gas and dust in the interstellar medium in galaxies, giving us fresh insight into the interplay between, for example, environment and feedback. Building on the success of the first ESOz conference in Sydney in February 2019, which was primarily focused on integral field unit (IFU) surveys, this meeting attempted to offer broader interdisciplinary connections.
It encompassed the Square Kilometre Array (SKA) Pathfinders in Australia, the ESO large surveys that are being or will be carried out from Paranal, and other instruments that are or will be delivering survey science, for example, the Atacama Pathfinder EXperiment (APEX), the Atacama Large Millimeter/submillimeter Array (ALMA), the Australian Astronomical Telescope (AAT), the extended ROentgen Survey with an Imaging Telescope Array (e-ROSITA), Vera C. Rubin Observatory, the Hubble Space Telescope (HST), the James Webb Space Telescope (JWST), and the 4-m Multi-Object Spectroscopic Telescope (4MOST). In addition to focusing on the synergies between instruments and surveys, it is crucial to consider results and predictions from simulations and models.

The conference was divided into five major themes that inspired the topics discussed each day[1,2]:

- **The baryon cycle in our own Galactic neighbourhood:** galactic archaeology, and the interstellar and circumgalactic gas in the Milky Way and Magellanic Clouds.
- **The local Universe:** the multi-phase baryon mass census (hot, cold and warm medium, stars and stellar halos), environmental and *in situ* physical effects.
- **Transients:** a nascent avenue of learning about galaxy evolution and the intergalactic medium, featuring, for example, fast radio bursts, gravitational waves and gamma-ray bursts.
- **Galaxies across time:** physical processes leading to quenching, angular momentum evolution, and black hole/galaxy co-evolution.
- **Cosmic Dawn and the Epoch of Reionisation:** the census of baryons and activity at $z > 4$, including galaxies, AGN and neutral hydrogen.

Figure 1. Conference photo (left) and conference dinner photo with all female participants (right).

Several current and upcoming instruments were discussed in the context of the windows they offer within the above broad science themes; for example, the Australian SKA Pathfinder (ASKAP), the Murchison Widefield Array (MWA), the South-African SKA pathfinder (MeerKAT), Very Large Telescope (VLT) instruments such as MAVIS[3] and 4MOST[4], both of which have significant Australian participation, ALMA, the AAT and the Australia Telescope Compact Array (ATCA).

Some key scientific results discussed during the meeting included recent breakthroughs in studies ranging from the Milky Way and Magellanic Clouds to the high-redshift Universe. In the last two years, astronomers have been able to quantify the outflow rate from the centre of the Milky Way associated with the Fermi bubble as well as from the Small Magellanic Cloud in several gas phases, including ionised and molecular gas. Gaia and ESO/AAT spectroscopic follow up have allowed a detailed understanding of the chemical structure and interaction history of the Milky Way. These results are key in placing the Milky Way into the broader context of galaxy formation. Recent years have also seen significant progress in closing the gap between the extragalactic background light and the contribution from galaxies from the far-ultraviolet to the far-infrared. Several talks also focused on the rise of environmental effects and the build-up of the Hubble sequence, extending studies to $z > 2$. A novel field that has gained significant interest is fast radio bursts (FRBs), which thanks to their dispersion measurement allow exquisite constraints on the density of the intervening intergalactic medium. Many breakthroughs presented highlighted the power of Australian and ESO facilities working in tandem. Particular examples of this include the VLT+ASKAP combination to study FRBs and intervening absorption systems to radio galaxies, and MWA+VLT+ALMA to study $z > 3$ radio galaxies and $z > 6$ reionisation sources, among others. Many talks showcased the power of current SKA pathfinders, which are already making significant progress, accomplishing in one day what used to take hundreds of hours.

Several problems were also discussed during the meeting. Many galaxy formation

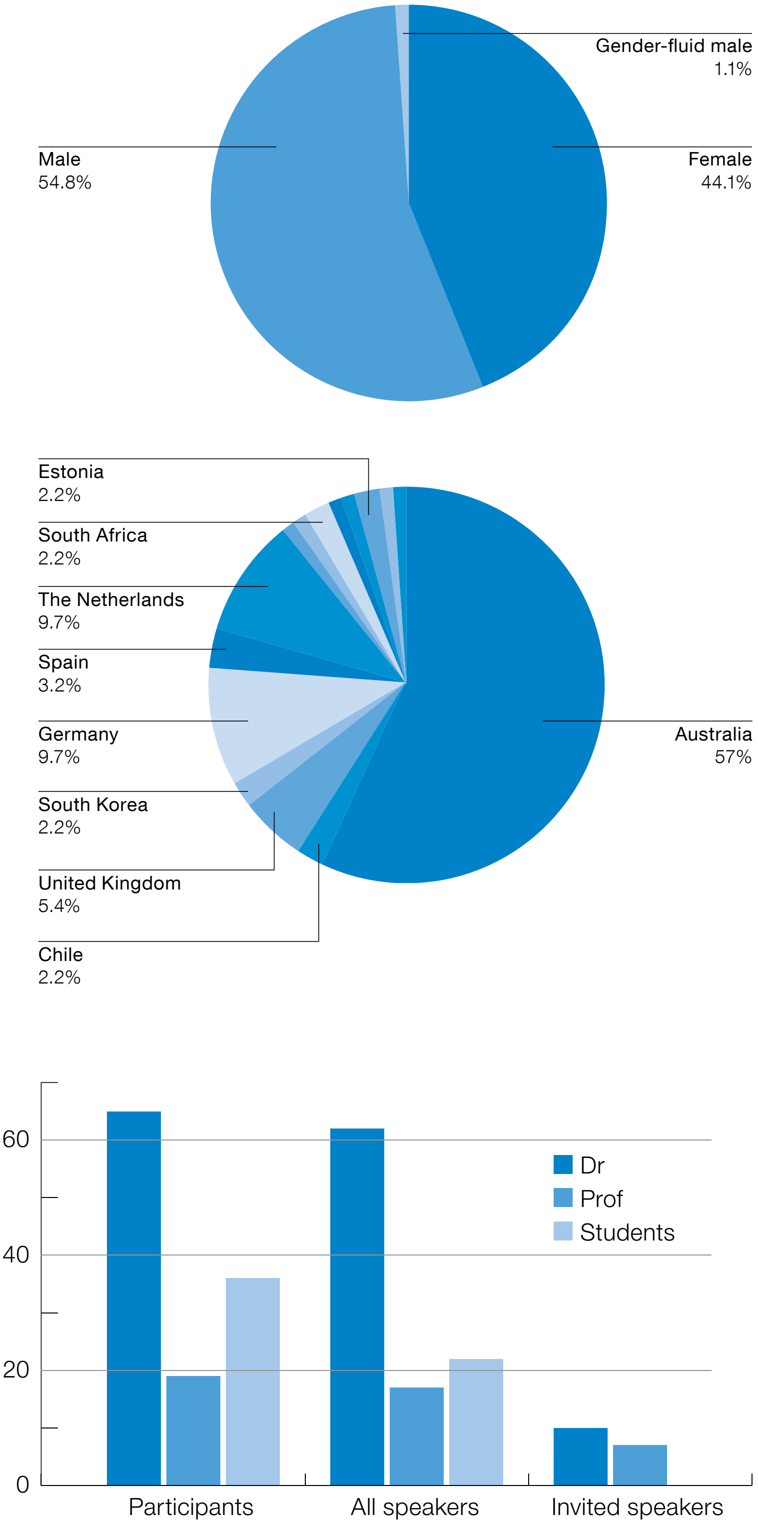

Figure 2. Distributions of gender (top-left panel), geography (top-right panel) and career stage (bottom panel). Though the first two were directly collected from the registration information of the participants, the latter was determined by their preferred title and hence is less robust.

simulations produce plausible universes from quite different physics, making it less clear how “success” is defined in the realm of theory and simulation. Perhaps the onus needs to be put back on observers to really uncover the most constraining measurements. There was some suggestion that tight 2D distributions such as the mass-size plane might be amongst the best to use when tuning simulation parameters. In addition, we are still a long way from fully modelling or observing gas in all its complex phases; for example, we rarely observe H_2 directly and assume uncertain X factors to convert from CO, [CI] or dust continuum. We also only have indirect detections of the weakly ionised hydrogen medium (WIHM), which seems to be the main source of baryons in the Universe. A contentious issue continues to be where theory and observation should meet, with advocates from each camp arguing that they are best placed to infer the H_2 distribution of galaxies.

Main conclusions

Several talks highlighted the fact that we are entering a new era of instruments and surveys that are planned simultaneously, bringing engineers and astronomers more closely together than ever before and maximising the scientific outcome of the investment. Most of the talks highlighted the need to study baryons and galaxies across the electromagnetic spectrum. This allows us to uncover a variety of phenomena, including outflows from the Milky Way and Magellanic Clouds, intergalactic gas around galaxies unveiled through FRBs and other transient phenomena, and accounting of baryons — stars, cold gas, neutral gas, ionised gas, dust etc. — across cosmic time, for example. The simulation talks summarised the main predictions as well as current areas of success and tension with observations. However, a cautionary note was that galaxy formation theory is not a fundamental theory and perhaps the focus should preferentially be on qualitative trends. The Australia–ESO community is clearly gaining momentum and these conferences have contributed tremendously to showcasing the benefit of this collaboration as well as promoting new ones.

Demographics and Remote participation

Demographics

During the organisation of the conference, we paid particular attention to making the event as inclusive as possible by controlling various biases in the selection of participants (for example, gender, seniority, and geographic distribution). The SOC decided to follow the guidelines of the first conference in the series (Zafar, De Breuck & Arnaboldi, 2019), which specify: (1) anonymising the contributed abstracts prior to ranking them; (2) asking the SOC members to declare any conflicts of interest with abstracts and remove themselves from reviewing those; and (3) anonymising the votes from the SOC. As with the previous ESOz conference, these measures naturally produced a programme with a good gender, geographic and career stage balance as shown in Figure 2. These results provide evidence that these measures, which are easy to apply, already go a long way towards systematically reducing implicit biases, and we recommend that future conference organisers adopt them.

Remote participation

Our conference took place during late February 2020 and its organisation was affected by the COVID-19 pandemic, even though it was relatively early in the evolution of the pandemic. More specifically, some of our participants were based in China, and by that date the Australian government had already imposed a ban on visitors from China. In addition, some participants had to cancel for last-minute personal reasons. The LOC worked hard to accommodate all participants who asked to give their talks remotely. The conference ended up with about 130 participants, approximately 10 of whom joined remotely while the rest were on site. We had five remote talks. One of the challenges we faced was that most remote speakers did not participate beyond giving their talks, which detracted slightly from the purpose of a “meeting” — only one participant was online remotely for the whole conference. This raised the question of how to encourage people to commit to a conference if they are physically elsewhere. A positive side, though, is that current platforms, such as Zoom, work well and make it possible to have a large number of remote participants. The current circumstances the world is suffering because of the pandemic have forced many countries to close their borders. The restrictions have led astronomers to cancel their travel plans, and it is clear that these issues are going to become more urgent and need to be addressed by the community as a whole.

Future

We note with sadness that this meeting was one of the last astronomy meetings to be hosted in Australia — and indeed the world — for the foreseeable future, owing to the COVID-19 pandemic which was dawning as the meeting took place. The consensus at the meeting was to host the next ESO–Australia conference at ESO in Garching, with a strong preference for it to be held during the European summer of 2021. There are some caveats over any future meeting dates because of the uncertainties around COVID-19, but the hope is that this goal is still realistic. The attendees at this meeting were certainly keen to come together again to further develop existing and new research connections between ESO and Australia.

Acknowledgements

We thank the sponsors of our conference: ESO, the Centre of Excellence ASTRO 3D, the International Centre for Radio Astronomy Research, Macquarie University, CSIRO Astronomy and Space Science (CASS). They allowed us to keep the conference fee relatively low by Australian standards. We also thank the Galaxies Journal for providing travel grants to two of our invited speakers.

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Links

[1] Presentations archived at Zenodo: https://zenodo.org/communities/esoaus2020
[2] Link to workshop programme: https://www.icrar.org/conferences/aus-eso-ii/
[3] MAVIS webpage: http://mavis-ao.org/
[4] 4MOST webpage: https://www.4most.eu/

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Fellows at ESO

Edmund Christian Herenz

A large number of professional astronomers felt somehow drawn to the nightly heavens since their early childhood days. I did not fall under this spell. My first encounter with astronomy was late in high school as part of the advanced physics curriculum. I enjoyed this course and it prompted me to attend a summer camp on astronomy. There, for the first time in my life, I peered through a telescope, but I did not feel much excitement — even with this aid to the eyes, the heavenly bodies looked nowhere near as interesting as in textbooks or magazines.

When I later enrolled at Humboldt University in Berlin to study physics, my dream was to become a solid-state physicist. This idea was largely nourished by my uncle, who followed this profession and with whom I spent many days in the lab as a kid. However, during my studies I realised that my level of manual skill was not fully compatible with sensitive laboratory equipment. In fact, it was so desperate that tutors already judged my practical exercises as successful when I managed not to break the experiment.

In search of something more suitable, I attended an astronomy lecture provided by Lutz Wisotzki from the Leibniz Institute for Astrophysics in Potsdam (AIP). This is when the spark of inspiration hit me: astrophysics is a subject where knowledge of physics can be used to understand processes on unimaginable scales and at distances far beyond the realm of ordinary human experience. Realising this made the whole physics curriculum even more exciting. Mechanics, thermodynamics, electrodynamics, quantum physics, special and general relativity — all these subjects provided tools that can be used to understand astrophysical phenomena.

Fuelled by a new passion for physics in general and astrophysics in particular I did an internship at the AIP. My tutor there was Bernd Husemann, who was just starting his PhD (Bernd would become an ESO fellow in Garching after his PhD). He showed me his newly acquired data from a recent observing run at the Calar Alto 3.5-m telescope and tasked me with helping him to reduce the data. These data consisted of Potsdam Multi-Aperture Spectrophotometer (PMAS) 3D spectroscopic observations of Seyfert galaxies. At the end of my internship we produced maps that displayed the motions of the ionised gas in those galaxies. Seeing galaxies like this for the first time, I understood immediately that 3D spectroscopic data will provide us with unprecedented knowledge about the processes that govern the physics of galaxy formation and evolution.

Edmund Christian Herenz

I wanted to be part of the research endeavour with 3D spectroscopy, so I did my bachelor's and master's projects at the AIP. At this stage, I was introduced to the Multi Unit Spectroscopic Explorer (MUSE) science team lead by Roland Bacon. There, I started to develop expertise in high-redshift emission line galaxies. In particular, I was tasked with thinking about ways of processing MUSE data to detect the highest-redshift galaxies within reach of this instrument (so-called Lyman-α emitters). Provided with the opportunity of doing a PhD at the AIP, these ideas then culminated in a 3D emission line source detection software: LSDCat (Line Source Detection and Cataloguing Tool). When MUSE was finally commissioned on the ESO Unit Telescope 4 (Yepun), it gave me a great sense of accomplishment that my software started to find numerous previously unknown high-redshift Lyman-α emitters. Most interestingly, the stellar continuum in these galaxies can sometimes be so faint that they are absent from even the deepest Hubble Space Telescope images. Owing to their distance and faintness, understanding the physics at play in high-redshift galaxies is notoriously challenging. Fortunately, galaxies that are similar to high-redshift systems do exist in the nearby universe. In my PhD I studied a sample of such nearby high-redshift analogues using PMAS. Then, as a postdoc with Matthew Hayes I could deepen my understanding of the fascinating processes in the interstellar- and circumgalactic medium of star-forming galaxies.

During my PhD and post-doctoral position, I was fortunate to participate in all the steps necessary for the creation of new empirical astrophysical insights: (1) pondering about astrophysical questions and the possible observational lines of attack towards answering them; (2) persuading a telescope time allocation committee to grant the needed observations; (3) performing the actual observations at the telescope; (4) reducing and analysing the observational data; and (5) publishing the results and their interpretation with respect to the original question. Moreover, by being a part of the MUSE Science Team I experienced first-hand how scientists and engineers from a multi-national background work together to realise a visionary technological idea. Experiencing astronomy and astrophysics from these various viewpoints sharpened my scientific mind.

My continuing fascination for astrophysics is sustained by future developments in ground-breaking technologies and I look forward to their application in uncovering new regions in discovery space. I have always valued that ESO is devoted to such visionary technological advances. I also value ESO as an organisation that continuously promotes and exercises the European Idea. For me, this idea not only encompasses freedom of travel and trade, but also has a transnational identity at its very heart. I strongly believe that such an identity is needed for a responsible and sustainable social commitment in a globalised world. Thus, I feel very honoured to be a fellow in an organisation embodying this idea.

As an ESO Chile Fellow, I spend 80 nights a year at the ESO Paranal Observatory site. I am assigned to UT4 — Yepun, the telescope at which MUSE is located. Being part of the operations at the world's best telescope with its advanced four-laser adaptive optics system is a unique experience. During long exposures, I regularly go out on the platform and admire the night sky. While the heavenly bodies did not manage to cast their spell on me as a child, now as an adult they make me feel like a child again, knowing that the Universe is full of wonders just waiting to be discovered.

Chiara Mazzucchelli

My passion for astronomy started as a very young kid, looking up at the dark night sky from the garden of my parents' house in the countryside in the north of Italy. By mere chance, I found an astronomy book in the small local library that caught my attention. I was in awe of the beautiful images from the recently launched Hubble Space Telescope, and I found it extraordinary that we could, with the power of mathematics and physics, (try to) understand and describe phenomena and objects so remote from us, literally "alien".

However, astronomy was not my only passion during my high-school years, I was very interested in literature, arts, history and related outreach activities, bringing tourists to visit beautiful castles and churches in Italy.


Chiara Mazzucchelli

I decided to pursue my interest in mathematics and physics in the end, enrolling in the physics programme at the University of Milano-Bicocca. I continued being involved in outreach activities, this time combining my passion for both history and astronomy by volunteering at the Observatory Messier 13 in Tradate (Varese), where I could show the sky to the public using small telescopes, a solar laboratory and a collection of historic solar clocks, joining science and the history of astronomy. The personnel at the observatory also observed and characterised asteroids with a 65-cm telescope. This was my first experience of working at a small observatory and in a team, and I thoroughly enjoyed the possibility of learning so much about telescopes and communication from experienced members of my local community.

After I got my bachelor's degree, I started a master's degree in astrophysics in Milan. Thanks to an exchange programme, I had the opportunity to work on my thesis at the Max Planck Institute for Astronomy (MPIA) in Heidelberg (Germany). Under the supervision of Roberto Decarli, I studied the environment of supermassive black hole candidates in quasars at low redshift, $z \sim 0.1$–0.7. I used multiband observations from the Bonn University Simultaneous CAmera (BUSCA) at the 2.2-m telescope in Calar Alto. I greatly enjoyed being able to develop my first fully executed project, thanks as well to the patience and enthusiasm of my supervisor. I particularly liked the lively exchange of ideas, discovering how new results could lead to new questions, and finding ways to try to answer them.

Therefore, I decided to pursue astronomical research to the next level, and I was glad to be able to start a PhD at the MPIA in Heidelberg, this time in the group led by Fabian Walter. During my PhD, I focused on quasars at very high redshifts, $z > 6$, in the first billion years of the history of the Universe. I find these sources extremely fascinating; they host incredibly massive black holes, and we observe galaxies that are already very evolved forming a large number of stars. How these sources could be formed in such a short time is still one of the more challenging and exciting questions in astrophysics. I was particularly interested in the characterisation of the large-scale environment of these sources, which can tell us about the dark matter distribution at very early times and unveil the first protoclusters. I was also involved in finding new high-z quasars, by mining multi-wavelength large-area sky surveys, especially the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS). Given the manifold nature of my project, I could work with different datasets, such as optical/near-infrared imaging and spectroscopy, from a variety of ground-based instruments and from space (for example, the Hubble and Spitzer Space Telescopes).

I considered myself particularly lucky to be able to work as part of "Team Quasar", collaborating and learning from many experts in the field, such as Eduardo Banados, Roberto Decarli, Emanuele Farina and Bram Venemans. Even as a new student, I felt my opinions were valued, and that no question was too stupid to be asked. My PhD was not a smooth ride, but the environment I worked in was fundamental to developing my trust and excitement as part of a research team.

Another important aspect of my PhD was that I could follow up many high-redshift quasars, observing directly at the telescope. I had the opportunity to spend many (> 30) nights at the MPG/ESO 2.2-m telescope at La Silla Observatory, operating all the instruments, especially the Gamma-ray Burst Optical/Near-infrared Detector (GROND) camera. There, I fell in love with the Chilean sky and the desert, and I realised that, despite the weariness of the long nights, an observatory on top a mountain in the desert was my "home away from home".

This encouraged me to apply for the ESO Fellowship in Chile, which I started in October 2018. At Paranal Observatory, I support operations on UT1 and UT2, and I am part of the Instrument Team of the infrared *K*-band Multi Object Spectrograph (KMOS). I am excited to learn more about this instrument and to make my contribution as, until now, I had no experience with IR integral-field spectroscopy. Now, I especially value the extremely rich and international environment at ESO, both in Vitacura and at Paranal. Working side-by-side with operators and engineers, I am in touch with instruments and operations in a way that would not be possible in many other institutes. I am extremely grateful also for all the personal support from the ESO staff in the last 1.5 years, which have not always been easy. On the other hand, the scientific environment in Santiago is rich and exciting, and allows me to touch ground and start new collaborations with teams at several universities. In my free time, I enjoy learning more about Chilean culture, visiting museums and theatres in Santiago, and Chile itself, exploring deserts and mountains and, of course, the beach.

Personnel Movements

Arrivals (1 April–30 June 2020)

Europe

Cortes Carvallo, Angela (CL)	Instrumentation Engineer
Dussuet, Thierry (CH)	Software Engineer
Guglielmetti, Fabrizia (IT)	ALMA Regional Centre Scientist
Seemann, Ulf (DE)	Instrumentation Engineer
Wilson, Christopher (UK)	IT Specialist — Security

Chile

Berrios, Lilian (CL)	Human Resources Assistant
Buie III, John Gilbert (US)	Web Application Developer

Departures (1 April–30 June 2020)

Europe

Dichirico, Canio (IT)	Electrical Engineer
Kalaitzoglou, Dimitrios (GR)	Electrical Engineer
Kurian, Kshama Sara (IN)	Student
Poci, Adriano (AU)	Student
Quattri, Marco (IT)	Mechanical Engineer
Riffald Souza Breuer, Jean-Paul (DE)	Student

Chile

André, Mylène (FR)	Communication Officer
Chacoff, Mercedes (CL)	Administrative Assistant
Gonzalez, Sergio (CL)	Electronics Engineer
Muñoz-Mateos, Juan Carlos (ES)	Operations Staff Astronomer
Nyman, Lars-Åke (SE)	Station Manager of Apex
Pérez Sánchez, Andrés Felipe (CO)	Fellow

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