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The SPECULOOS Southern Observatory
ALMA Observations of the Epoch of Planet Formation
The Early Growth and Life Cycle of Galaxies with KMOS^{3D}
Riccardo Giacconi (1931–2018)

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The SPECULOOS Southern Observatory Begins its Hunt for Rocky Planets

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The SPECULOOS Southern Observatory (SSO), a new facility of four 1-metre robotic telescopes, began scientific operations at Cerro Paranal on 1 January 2019. The main goal of the SPECULOOS project is to explore approximately 1000 of the smallest ($\leq 0.15\,R_\odot$), brightest ($K_{mag} \leq 12.5$), and nearest ($d \leq 40$ pc) very low mass stars and brown dwarfs. It aims to discover transiting temperate terrestrial planets well-suited for detailed atmospheric characterisation with future giant telescopes like ESO's Extremely Large Telescope (ELT) and the NASA James Webb Telescope (JWST). The SSO is the core facility of SPECULOOS. The exquisite astronomical conditions at Cerro Paranal will enable SPECULOOS to detect exoplanets as small as Mars. Here, we briefly describe SPECULOOS, and present the features and performance of the SSO facility.

Search for Planets EClipsing ULtra-cOOl Stars (SPECULOOS)

One of the most thrilling questions posed by humankind is whether inhabited worlds similar to Earth exist elsewhere in the Universe. The most direct way of answering this question is through the detection and detailed atmospheric characterisation of terrestrial exoplanets orbiting in the habitable zones of nearby stars. The nearest ultra-cool dwarf (UCD) stars represent a unique opportunity to reach this goal within the next couple of decades. UCD stars are very low mass stars at the bottom of the main sequence, with masses approximately 10% that of the Sun, sizes similar to Jupiter, effective temperatures lower than 2700 K, and luminosities less than one thousandth that of the Sun.

The habitable zones in these systems are very close to the host stars, corresponding to orbital periods of only a few days. This proximity to the host star maximises the transit probability and the likelihood of detecting habitable planets. In addition, an Earth-sized planet transiting a small UCD star produces a 1% transit signal, 100 times deeper than that of an equivalent transit around a Sun-like star, and well within the reach of ground-based telescopes. With these properties, it is possible to characterise the atmospheres of UCD habitable zone planets — including the potential detection of spectroscopic biosignatures — with forthcoming giant telescopes such as ESO's ELT (Rodler & López-Morales, 2014) and the JWST (Kaltenegger & Traub, 2009).

SPECULOOS[1,b] (Principal Investigator: Michaël Gillon) is a new photometric survey based on a network of 1-metre-class robotic telescopes. It aims to seize the opportunity to detect temperate terrestrial planets transiting nearby UCDs that are bright enough in the near-infrared to make possible the atmospheric characterisation of their planets in the near future (see Gillon et al., 2018; Delrez et al., 2018a; Burdanov et al., 2017).

Figure 1. The four 1-metre telescopes Io, Europa, Ganymede, and Callisto (from right to left)[a] of the SPECULOOS Southern Observatory starting the night under Paranal's sky.

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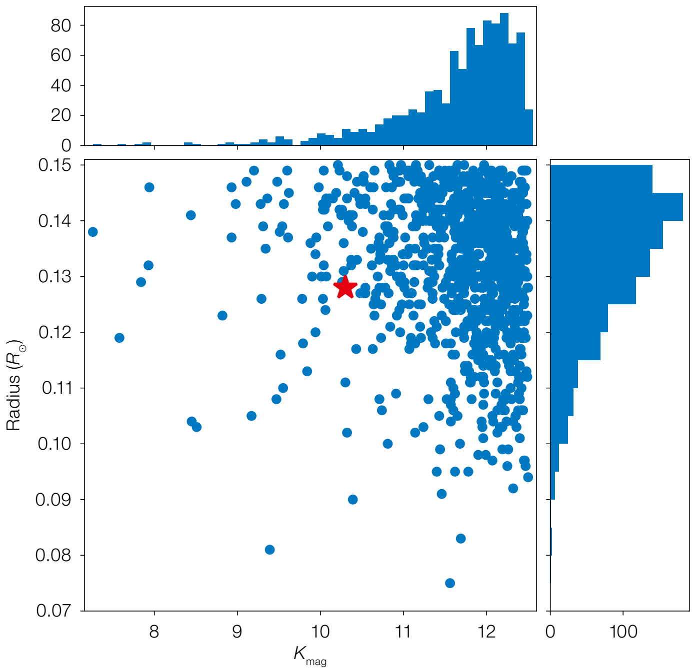

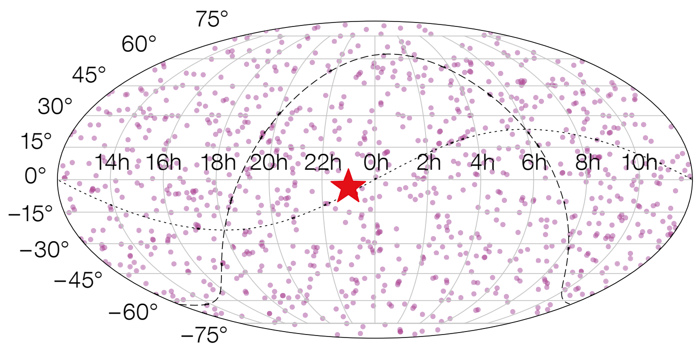

Figure 2. Left: The distribution of the SPECULOOS target sample in brightness and estimated radius. Right: The locations of these targets in equatorial coordinates, with the Galactic and ecliptic planes indicated as dashed and dotted lines, respectively. In both panels, TRAPPIST-1 is shown as a red star.

The target sample and observing strategy

The SPECULOOS target sample includes all UCD stars within 40 pc of the Sun that have a *K*-band magnitude less than 12.5 and an estimated radius less than 15% of the Sun's. These limits in *K*-band and radius correspond to the properties that allow the atmospheric characterisation of temperate Earth-sized planets with JWST. Cross-matching the catalogues from the second data release (DR2) from the ESA Gaia mission with the Two Micron All-Sky Survey (2MASS), we identified about 1000 targets across the sky, of which ~ 90% are very late M-dwarfs and ~ 10% are L-dwarfs.

Our targets are evenly distributed over the sky (Figure 2), which means that they have to be monitored individually. Fortunately, the short orbital periods of planets in the habitable zones of UCDs (~ 1 week) translate into a required photometric monitoring period for each star that is much shorter than the equivalent monitoring period for an Earth-Sun twin (~ 1 year). Consequently, SPECULOOS should complete its extensive transit search for planets around 1000 UCD targets within a 10-year window.

Because of their low temperatures, UCDs are faint in the optical, and their spectral energy distributions peak at near- and mid-infrared wavelengths. Our signal-to-noise analysis demonstrated that 1-metre-class telescopes on a dry site with good seeing, equipped with near-infrared optimised CCD cameras (providing high quantum efficiencies out to 1 μm) would be sufficient to achieve the required photometric precision (< 0.1%). We validated this strategy through a six-year prototype survey that we performed with the southern 0.6-metre telescope of the TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST) at ESO's La Silla observatory (Jehin et al., 2011; Gillon et al., 2011). This led to the spectacular discovery of the TRAPPIST-1 [2] exoplanetary system (Gillon et al., 2016, 2017).

In addition to high photometric precision, observations of each target must be taken nearly continuously over 10–25 nights to assure the detection of low-amplitude transits from planets orbiting in UCD habitable zones. These continuous observations not only maximise the photon counts but also minimise systematics and improve photometric reliability by allowing us to keep all of the stars in a particular field of view on the same pixels of the detector over the course of an entire night. Continuous observations also enable the robust detection of short-duration transits (as little as 15 minutes) expected for planets around UCDs with very short orbital periods (≤ 1 day).

To observe 1000 UCDs with SPECULOOS over the monitoring periods described above requires a total of ~ 20 000 nights of survey data. This can be achieved in ~ 10 years with a network of two facilities, one in each hemisphere and comprising four telescopes each, assuming a global efficiency of 70% (i.e., a 30% time-loss due to bad weather and technical problems).

These considerations drive the instrumental conceptual design of our survey: a network of ground-based 1-metre-class optical telescopes equipped with near-infrared optimised CCD cameras, monitoring each UCD individually and continuously for a duration long enough to efficiently and thoroughly probe its habitable zone for transiting planets. Whilst we are still in the process of deploying two telescopes in the northern hemisphere, our core facility, the SPECULOOS Southern Observatory (SSO), is now fully operational at Paranal. After a two-year development phase and two years of installation and commissioning, the facility is now starting routine operations.

The SSO site

With its low humidity (80% of nights with < 4 mm precipitable water vapour), Peter Aniol

Figure 3. The SSO is visible to the left. It neighbours the NGTS facility and is downhill from the VISTA peak. The VLT is to the right on top of Cerro Paranal while the basecamp is in the background, in the shade at the middle of the image.

excellent seeing, photometric conditions (78% of nights are photometric), and logistical infrastructure, Paranal was recognised early on as the preferred site for the installation of the SSO. Following discussions with ESO and its Scientific Technical Committee (STC), the agreement for the construction of the SSO at Paranal was signed by the then Director General Tim de Zeeuw on 30 March 2015. After a two-month seeing monitoring campaign to validate the site (seeing was better than 1.5 arcseconds for 90% of the nights), it was decided to install the SSO on a spot (see Figure 3c) below the VISTA peak and close to the Next-Generation Transit Survey (NGTS) — another exoplanet survey facility (Wheatley et al., 2018).

The telescopes and domes

The SSO is composed of four identical robotic 1-metre Ritchey-Chrétien telescopes built by the German ASTELCO company[3]. For each telescope, the 1-metre diameter primary mirror has an *f*/2.3 focal ratio and is coupled with a 28-centimetre diameter secondary resulting in a system with a combined *f*/8 focal ratio. Both mirrors are coated with pure aluminium. The telescopes have a compact and open design with a lightweight optical tube assembly made of steel, aluminium and carbon fibre components (see Figure 4).

This design provides high wind resistance, enabling observations in wind speeds reaching 50 km h^{-1}. The focusing of each telescope is achieved through motorised axial movement of the secondary mirror to an accuracy of 5 µm. Each telescope is associated with a robotic equatorial ASTELCO New Technology Mount NTM-1000. This mount uses direct-drive torque motors, which allows fast slewing (up to 20 degrees s^{-1}), accurate pointing (better than 3 arcseconds) and tracking accuracy better than 1 arcsecond over 10 minutes without an autoguider. A key component of our strategy to achieve high photometric precision is to keep our target stars on the same pixels for an entire exposure sequence. This is done using an updated version of the DONUTS autoguiding system described by McCormac et al. (2013). This technique relies on a reference

Figure 4. Commissioning of Io and Europa in the ASTELCO assembly hall in Munich.

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image of each science field. The reference image is summed along the x and y directions, creating two 1D reference image projections. A pair of 1D comparison projections is created for each subsequent science image and the guide correction is measured from a pair of cross-correlations between reference and comparison in both x and y directions. This allows a self-guiding precision better than 0.5 pixels (0.15 arcseconds) root mean square (RMS) over tens of nights for the same target.

Each telescope is enclosed in a 6.25-metre-diameter circular building surmounted by an automated hemispheric wide-slit dome with sliding doors (see Figure 5), made and equipped with an automation system from ASTELCO. The domes are made of aluminium, painted white outside to minimise internal heating during the day, and dark inside to minimise reflections during the night. The dome is slave to the telescope and a complete azimuth rotation takes less than one minute. Each building also includes a small control room that we use for commissioning activities, equipment storage, and the telescope control cabinets and computers. The distance between the domes is optimised to prevent vignetting of any telescope by another, down to 20 degrees above the horizon.

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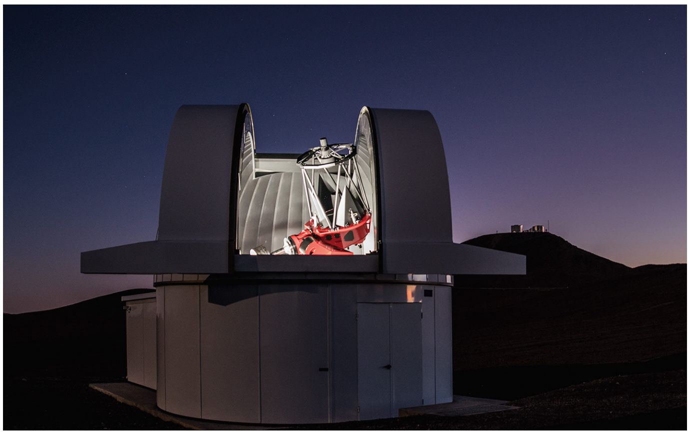

Figure 5. The Io 1-metre robotic telescope unit in its 6.25-metre dome.

The cameras and filters

Each telescope is equipped with an Andor iKon-L thermoelectrically cooled camera with a near-infrared optimised, deep depletion 2k × 2k e2v CCD detector (13.5 µm pixel size). The field of view on the sky is 12 × 12 arcminutes, yielding a pixel scale of 0.35 arcseconds pixel^{-1}. The camera can be cooled down to – 100° C (via five-stage Peltier cooling) but it is usually operated at – 60° C with a dark current of ~ 0.1 electrons s^{-1} pixel^{-1}. The detector provides high sensitivity from 350 nm (near-ultraviolet) to 950 nm (near-infrared), with a maximum quantum efficiency of 94% at both 420 and 740 nm. The camera also has very low fringing in the near-infrared (< 1%) thanks to both the wedge design of the window and the e2v proprietary fringe suppression technology applied to the detector. There are four readout speeds available, up to 5 MHz, with various gains. The observations at each telescope are performed using the same 1 MHz readout mode, no binning and a gain of about 1.1 electrons ADU^{-1}, which provides a low readout noise of about 6.0 electrons.

Each camera has its own filter wheel from Finger Lakes Instrumentation (model CFW3-10), allowing 10 different 5 × 5 cm filters. A selected set of broad-band filters, all manufactured by Astrodon company, is available on each telescope: the Sloan *g'r'i'z'* filters and two special exoplanet filters; the near-infrared luminance *I+z* filter (transmittance > 90% from 750 to beyond 1000 nm); and a blue-blocking filter called Exo (transmittance > 90% from 500 to beyond 1000 nm). Some of the telescopes also provide broad-band Johnson-Cousins B, R_C and V filters, the Sloan *u'* filter, and the Hα, S II and O III narrow-band filters.

A robotic and safe observatory

Building on the experience and operational scheme of TRAPPIST (Jehin et al., 2011, Gillon et al., 2011), the SSO is nearly fully robotic and can be controlled remotely via a secure Virtual Private Network (VPN) connection between Paranal and the University of Liège. Observing plans, consisting of simple text files (one for each target) linked to each other, are automatically generated and submitted daily by a scheduling script to the ACP Expert Observatory Control Software[4], which is installed on the control computer of each telescope unit. ACP is the main automation software working in combination with the various subsystems, and it automatically handles every aspect of the observations: startup and shutdown procedures (including flat fields and other calibrations), pointing and centring of the targets, autofocusing, filter wheel management, image setup and acquisition sequences, autoguiding via DONUTS, target chaining, and other operations.

ACP is also in charge of the shutdown of the observatory in case of bad weather. Each telescope unit is independent and is equipped with its own weather station[d], which monitors in real time the cloud cover, sky temperature, wind speed (≤ 50 km h^{-1}), humidity level (≤ 80%), dew point, and the amount of daylight. These weather stations also include a moisture sensor that is able to detect rain and snow. They are connected to ACP and can trigger a clean and automatic termination of observations (closing the dome and parking the telescope) in bad weather conditions. The weather stations are also directly wired to the domes for emergency closure in case ACP does not trigger it. In addition, each dome is equipped with rain and light sensors, working independently from the telescope control computer for redundant safety.

Several IP power sockets are connected to the electrical devices inside the domes to allow remote rebooting (or shutdown) when necessary. Each observatory unit is equipped with an uninterruptible power supply (UPS) that can hold each telescope in operation for about 8 hours. To guarantee safe and optimal operation, one operator initiates the startup procedure before twilight, making sure that

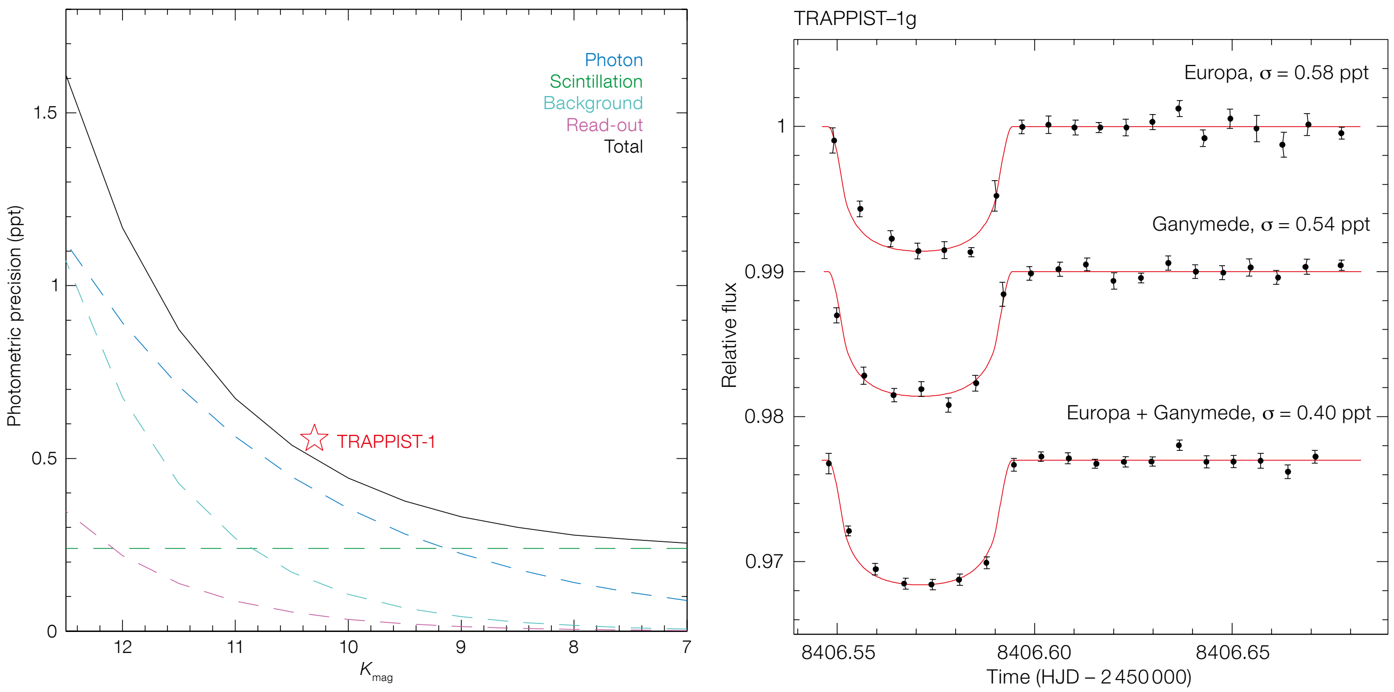

Figure 6. Left: Photometric errors per time bin of 0.005 d (7.2 minutes) computed for an M8-type dwarf observed by one SSO telescope as a function of its *K*-band magnitude. The different contributions to the errors are shown as dashed coloured lines. The photometric precision measured for TRAPPIST-1 is illustrated as a red star symbol. Right: Light curves, binned per 0.005 d, of a transit of the temperate terrestrial planet TRAPPIST-1g observed by Europa (top) and Ganymede (middle), and the combined light curve Europa + Ganymede (bottom).

the weather and telescopes are safe and in working condition after performing diagnostic checks. At the end of the night, the operator makes sure the telescopes are closed and secure. An operational webpage receives live information about the telescopes and the weather status as well as real-time images of the night sky and dome webcams. This setup allows us to easily keep an eye on the observatory.

Dataflow and pipeline

Each telescope generates between 250 and 1000 images per night with typical exposure times of 10–50 s, corresponding to between 4 and 16 Gb of data. The data are saved locally on a dedicated computer for each telescope and are initially processed by a local pipeline. The data are automatically transferred to the ESO archive and then retrieved to be processed by a dedicated pipeline which produces calibrated light curves that are then used to compute differential photometry for the target star.

In addition to producing a unique photometric database for a large sample of nearby UCDs, the SPECULOOS dataset is also valuable for the astronomical community, as it provides densely-sampled photometric monitoring over long periods (10–20 nights) over a total survey field of view of 24 square degrees with excellent spatial sampling in the near-infrared. By agreement with ESO, we will provide public access to the photometric data gathered with the SSO after a one-year proprietary period. Reduced images, as well as extracted light curves of all point-sources detected by our reduction pipeline, will be made available to the community via the ESO archive (under the programme ID 60.A-9009).

Photometric performances

Figure 6 shows the photometric precision expected for each SSO telescope for an integrated exposure of 7.2 minutes (7 exposures of 50 s + overheads) in the "*I*+*z*" filter for M8-type dwarfs with *K*-magnitudes covering the whole range of SPECULOOS targets. Uncertainties take into account the transparency of the sky at Paranal, mirror reflectivity, the quantum efficiency of the CCD cameras cooled to – 60° C, and the transmittance of the filter and of the CCD window. We assume pure white noise (photon noise, dark current, background, scintillation, and readout), an airmass of 1.5, a typical seeing of 1 arcsecond, and a photometric aperture of 2-arcsecond radius.

Figure 6 also shows a transit of TRAPPIST-1g observed by Europa and Ganymede. TRAPPIST-1g orbits around a *K* = 10.3 M8-type dwarf, and our photometric performance calculator predicts a precision of 0.51 ppt[e] for each total integration of 7.2 minutes. Our observed light curves, divided by the best-fit transit models and also binned by 7.2 minutes, have standard deviations of 0.58 and 0.54 ppt — only slightly larger than the predicted value and consistent with a correlated, "red-noise floor" of 0.2–0.30 ppt. Combining the two light curves reduces the standard deviation to 0.4 ppt, scaling by ~ √2 as expected. This impressive photometric precision validates the scientific potential of the SSO. Indeed, the transit of a temperate Earth-sized planet should be in the range 3.8–13.5 ppt, and should have a typical duration of 30 to 60 minutes. Figure 6 shows that our photometric precision is sufficient to robustly detect such transits for every star in our UCD sample, irrespective of atmospheric or instrumental red noise. For our brightest and smallest targets, we expect to be able to detect transits of planets as small as Mars (depth of ~ 3 ppt in front of a 0.08 $R_{\odot}$ star).

A global network of robotic telescopes

SPECULOOS will eventually consist of five nodes, with the SSO being the primary node. The other nodes are: the SPECULOOS Northern Observatory (SNO), which will consist of at least one 1-metre telescope to be installed in Spring 2019 at Teide Observatory in Tenerife (Canary Islands); SAINT-Ex, a new robotic 1-metre telescope that is being installed at San Pedro Mártir Observatory (Mexico), and which will partially contribute to SPECULOOS; and finally, the two 60-cm robotic telescopes TRAPPIST-South (La Silla Observatory, Chile) and TRAPPIST-North (Oukaïmeden Observatory, Morocco), which devote ~ 25% of their time to SPECULOOS, focusing on about 100 of the brightest targets.

The discovery of TRAPPIST-1

The SPECULOOS project started in 2011 as a pilot survey using TRAPPIST-South (Gillon et al., 2011), with a limited target list composed of the 50 brightest southern ultra-cool dwarf stars. The goal of this pilot was to assess the feasibility of the project, but the survey achieved much more than anticipated. It detected a spectacular planetary system that we named TRAPPIST-1[2], which is composed of seven Earth-sized planets in temperate orbits ranging from 1.5 to 19 days (Gillon et al., 2016, 2017). At least three of these planets orbit within the habitable zone of the star, and each of them is particularly well-suited for a detailed atmospheric study with JWST. Thanks to the resonant and transiting configuration of the system, the masses and radii of the planets could be precisely measured (Grimm et al., 2018; Delrez et al., 2018b). The resulting densities suggest that most of the planets have a rocky composition with a volatile content significantly larger than that of Earth.

The detection of TRAPPIST-1 from a target list of only 50 objects, and the apparently low densities of most of its planets, suggest that compact systems of water-rich rocky planets could be very frequent around UCD stars (He, Triaud & Gillon, 2017), in agreement with recent theoretical predictions. Should this be confirmed, it implies that SPECULOOS will find many other TRAPPIST-1-like systems, and eventually produce a catalogue of several dozen temperate rocky planets that are well suited for detailed atmospheric characterisation with the next generation of major astronomical facilities.

Acknowledgements

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Links

[1] The SPECULOOS project: http://www.speculoos.uliege.be/
[2] The TRAPPIST-1 planetary system: http://www.trappist.one/
[3] ASTELCO Systems: http://www.astelco.com/
[4] ACP observatory control software: http://acp.dc3.com/
[5] The TRAPPIST project: http://www.trappist.uliege.be/

Notes

[a] Since we expect the typical planetary systems around UCDs to be scaled-up versions of the Jovian satellite system (with terrestrial planets replacing the Galilean moons), we decided to name the four telescopes Io, Europa, Ganymede, and Callisto.
[b] Speculoos are also delicious cookies that are traditionally baked in Belgium for consumption around St Nicholas's day on 6 December.
[c] The coordinates of the site are: latitude −24°36′56.2″ and longitude −70°23′25.4″
[d] The Boltwood Cloud Sensor II from Diffraction Limited company
[e] ppt: part-per-thousand (i.e., 0.1%)

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The Life and Times of AMBER: The VLTI's Astronomical Multi-BEam combineR

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The sharpest images on Paranal are produced by the beam-combining instruments of the Very Large Telescope Interferometer (VLTI). Currently, the VLTI is close to completing a transitional period, moving away from the first generation of instruments (AMBER, MIDI) and offering new instruments and subsystems to the community. In this article, we report on the life and achievements of the recently decommissioned, near-infrared beam combiner instrument AMBER, the most prolific optical interferometric instrument to date.

AMBER, a three-telescope combiner

AMBER was one of three ambitious, general-user, interferometric instruments proposed in 1997 for implementation on the VLTI at Paranal (Paresce et al., 1996), following the recommendations of the Interferometry Science Advisory Committee to ESO. In optical interferometry, new instruments are scientifically inaugurated via their "first fringes", which is the interferometric equivalent of "first light". By the early 2000s, the integration of ESO's interferometer into the VLT architecture was on track.

The first Paranal interference fringes were produced by the VLT INterferometer Commissioning Instrument (VINCI) and MID-infrared Interferometric instrument (MIDI), instruments that combined the light from two telescopes. VINCI's purpose was to commission the interferometer's infrastructure. MIDI, on the other hand, was the first scientific instrument in operation using the VLTI in conjunction with the 8.2-metre Unit Telescopes (UTs). The second scientific VLTI instrument to arrive on Paranal was AMBER. It had been conceived as a potential sea change in optical interferometry, exploiting the idea of spectro-interferometry — obtaining spatial information on milliarcsecond scales at high spectral resolution. It comprised three spectral settings, including a high spectral resolution of R = 12 000, and was foreseen to work at a high sensitivity and with high visibility accuracy in three infrared atmospheric windows (J-, H-, and K-bands). Yet, arguably its most important asset was the capacity to combine the light beams from three separate telescopes at long baselines, a novelty in long-baseline optical interferometry which allowed millarcsecond-resolution images to be synthesised at high spectral resolution.

The consortium of four institutes driving the AMBER project consisted of the Observatoire de la Côte d'Azur (OCA: the Principal Investigator institute) in Nice, the Laboratoire d'Astrophysique de l'Observatoire de Grenoble (LAOG at the time, now called IPAG), the Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn, and the Osservatorio Astrofisico di Arcetri in Florence. It built on the European expertise of designing two-telescope combiners capable of exploiting spectro-interferometry and the usage of single-mode fibres. Conceptually, to advance from two-telescope to three-telescope combiners may seem a small step, but scientifically it constituted a leap forward.

The crucial consideration is to provide access to the observational quantity called the closure phase. The absolute phase of incoming light waves is scrambled by atmospheric turbulence, resulting in distortion over a pupil and global phase shifts between the apertures in the array (called the piston). The degree and frequency of the scrambling increases towards shorter wavelengths. As a result, the coherence time of the incoming wave ranges from a few milliseconds to (at best) some tens of milliseconds in the optical regime. There is no way to beat the turbulence and recover the phase without additional aids. When combining three telescopes arranged in a closed triangle one can retrieve a new observable by adding the phases. This resulting closure phase is invariant to atmospheric perturbations, as the atmospheric phase noise terms from each individual telescope cancel out. The technique was first applied in radio interferometry. Physically, the closure phase quantity is a proxy for the degree of asymmetry in the science target. Closure phase information is a pre-requisite to reconstructing images from interferometric observables (for example, Jennison, 1958; Baldwin et al., 1996) and AMBER was the first instrument at the VLTI to deliver it.

AMBER produced clear first fringes of the star θ Centauri on the night of 20 March 2004 using two telescopes at a baseline of 64 metres, marking a milestone after seven years of work. The instrument was offered to the community for the first time in observing period 76 (starting October 2005), fed by the large apertures of the UTs.

Optical principle and early years

AMBER's design corresponds broadly to an optical configuration similar to the one that creates fringe patterns in a Young's interference experiment, i.e., overlapping images coming from multiple telescopes (or beams). Most importantly, before the light is recombined, each light beam is guided through a single-mode fibre. A single-mode fibre acts as a spatial filter and rejects the distorted part of the wavefront, leading to a flattened exit wavefront. The phase fluctuations are traded against fast intensity fluctuations (which are recorded) and a global piston (which is measured from the slope of the dispersed fringes). Hence, AMBER implements three photometric channels for the simultaneous monitoring of the beam intensity for each telescope beam. Recombination, and with it the production of fringe patterns, is done after forming three exit pupils. The exit pupils are physically placed in a non-redundant manner such that the set of three contained spatial frequencies in the final interferometric image are fixed (i.e., non-homothetic) but different and identifiable. The four beams — three intensity monitoring beams and the one interferometric beam containing all the information for the three baselines — are then spectrally dispersed before detection (Petrov et al., 2007).

The integration of AMBER operations into the complex VLTI and telescope architecture was an iterative process (see Mérand et al., 2014). For example, operations began with the UTs equipped with the Multiple Application Curvature Adaptive Optics (MACAO) guiding systems, before the arrival of the versatile Auxiliary Telescopes (ATs). The ATs were commissioned in the summer of 2006 and first offered in April 2007 with a limited set of baselines. On the VLTI side, the injection of the light into the instrument's single-mode fibres was optimised by controlling the tunnel tip-tilt inside the VLTI laboratory using the InfraRed Image Sensor (IRIS). This sensing sub-system was operated from 2006 onwards but using the telescopic XY table as a corrective system. As a result, it operated at a sub-optimal slow rate of about 1 Hz, but it was nonetheless quickly seen as a mandatory prerequisite for improved beam injection.

After the first couple of years of operation it became clear that AMBER was not fulfilling all of its potential on the VLTI. As the first VLTI instrument to possess high spectral resolution, and therefore to require longer integration times, it demanded much more from the VLTI infrastructure than its predecessors. Flux injection and phase stability had to be significantly improved. The observation overheads were large, the quality of the high-spectral-resolution data was degraded, and the sensitivity was limited. These problems and others were tackled thanks to increased efforts from the AMBER consortium in 2007–2008, and through the continuous improvement of the VLTI infrastructure.

A report analysing the accuracy in absolute visibility, closure phase and differential phase identified critical software and hardware improvements required by AMBER (Malbet et al., 2008). The main modifications in AMBER were the replacement of its polarisation filters which were responsible for parasitic Fabry-Perot fringes in all the spectro-interferometric measurements, and improvements in its operation and maintainability. On the VLTI, after a significant improvement in the delay line models, a continuous effort resulted in the progressive reduction of the vibrations in the coudé trains of the UTs. A decisive factor was the implementation of a faster loop to counter the flux dropouts seen in the instrument – a higher correction rate was made possible by offloading the measured IRIS tip-tilt to the feeding optics of AMBER. AMBER's performance could be further improved thanks to the arrival of the Fringe-tracking Instrument of NIce and TOrino (FINITO) (Haguenauer et al., 2008).

Arrival of FINITO

The art of fringe tracking was introduced into AMBER operations for the Period 80 call for proposals in October 2007. The purpose of fringe tracking is to nullify the fringe movement caused by atmospheric turbulence which blurs the contrast of the fringes. With FINITO, longer detector integration times could now be employed. Longer integration of fringe patterns allows the observation of targets at a higher spectral resolution, or of fainter sources, or allows a lower intrinsic fringe contrast to be measured. Additionally, longer detector integration times also allow the full detector to be read out, increasing the spectral range covered by the observations. Fringe tracking was implemented in the VLTI by means of the separate instrument FINITO (Gai et al., 2004). Its purpose was to measure the broad-band fringe jitter at kHz frequency in the *H*-band. The FINITO signal was processed and injected back into the VLTI in real time via the Reflective Memory Network architecture. As of Period 83 (April 2009) standard AMBER operations for medium and high spectral resolution were done in conjunction and simultaneously with FINITO. Since 2011, the FINITO data have been delivered alongside the AMBER ones for optimised data reduction and post-processing purposes. With the advent of GRAVITY fringe tracking has become an integral part of the science observations and the data from the fringe tracker are used in the data reduction process.

Continual enhancements of AMBER and the VLTI resulted in steady improvements of the limiting magnitude and operational efficiency. AMBER's self-coherencing was introduced in April 2012 for the low-resolution setup. This mode allowed automatic real-time fringe centring at a relatively low cadence when fringe tracking with FINITO was not possible (for example, because of seeing conditions or low source flux). The instrument intervention performed at the end of 2012 changed the spectrograph beamsplitter that caused internal reflections; this resulted in almost a 30% improvement in throughput in the interferometric channel. Better polarisation control, by means of birefringent lithium niobate ($LiNbO_3$) plates, was introduced in October 2014, following an earlier implementation in the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER). Such plates allow the equalisation of the phase difference between the two polarisation stages and add them incoherently, improving the sensitivity by a factor of nearly two. At the same time the observing efficiency improved dramatically by a factor of three since the start of operations, resulting in much shortened execution times of 20 minutes per Observation Block (OB), down from one hour.

Science delivered

ESO's AMBER and VLTI infrastructure delivers observable quantities that reveal the wavelength-dependent structure and geometry of astrophysical sources at a very high angular resolution: indeed, the best available from any of the ESO instruments. At the wavelength of operation, AMBER can reach angular resolutions of the order of 1 milliarcsecond. The differential phase accuracy allowed photocentre displacements as small as 10 microarcseconds to be measured, for example, in the alignment between the stellar rotation axis and the orbits in the Fomalhaut debris disc system (Le Bouquin et al., 2009). The superb angular resolution allows breakthrough science by delving into spatially unexplored regions on stellar surfaces, in the circumstellar environment of young and evolved stars, and around the active nuclei of galaxies.

ESO's Telescope Bibliography telbib provides the following statistics for the science legacy of AMBER. Up to October 2018, AMBER data contributed to 153 peer reviewed science papers. This number nearly equals the total number of science papers produced with data from MIDI, which was decommissioned in March 2015. The number of papers makes these two instruments the most productive in terms of science papers produced using data from a long-baseline optical interferometry facility. Over the period 2015–2017, about ten papers per year were published with AMBER data; given that telbib publication analyses estimate an average lag time between the execution of a programme and the publication of a paper of approximately 5.4 years for 50% of the data, it is not unreasonable to expect a few tens of peer-reviewed AMBER papers to see the light of day in the coming years.

Regarding instrument modes, the relative demand for the various AMBER spectral settings varied substantially, with the low-resolution and medium-resolution setups vying for dominance. The low-resolution time requested strongly dominated up to Period 88, with over 80% of the demand between Periods 79 and 82. After Period 88, the medium-resolution settings (*H*- and *K*-band) became more popular, leading to approximately 60% of the time requested after Period 94. The high-spectral-resolution setting request fluctuated around 20% of the total time after Period 82, coinciding with the introduction of FINITO to VLTI and UT operations.

The topics of the science papers deal almost exclusively with stellar evolution, in particular star formation and young stars, late evolutionary stages of intermediate- and low-mass stars (for example, asymptotic giant branch [AGB] stars) and high-mass stars. Their fractional contribution by sub-category is presented in Figure 1, and we highlight some of these science cases in the next section.

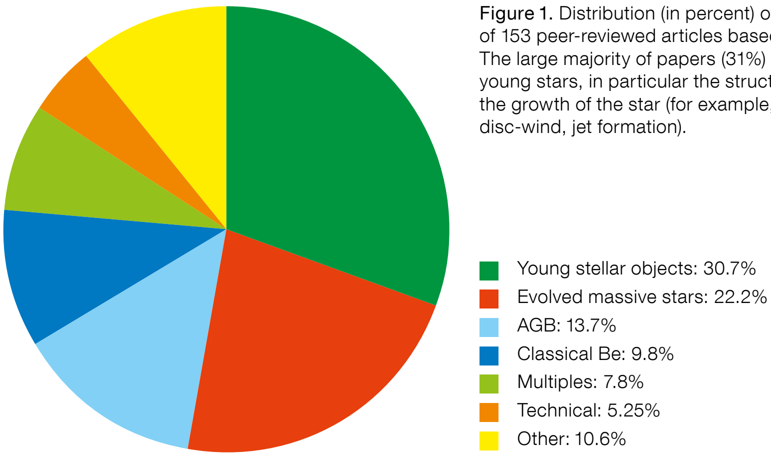


Figure 1. Distribution (in percent) of science topics of 153 peer-reviewed articles based on AMBER data. The large majority of papers (31%) are centred on young stars, in particular the structures that allow the growth of the star (for example, accretion disc, disc-wind, jet formation).

The sub-topics cover a wide range of science cases, from the evolution of cool evolved stars, concentrating on circumbinary discs of post-AGB stars and supergiant B[e] stars, the inner wind regions in neutral and ionised gas of post-red supergiants and unstable hypergiants, and the nebulae of Wolf-Rayet stars.

One example of exploiting aperture synthesis imaging to better understand evolved high-mass stars is the image of the well-known luminous eruptive star η Carinae, shown in Figure 2. It is one of the first direct images of the innermost part of the wind-wind collision zone, a key feature of the observed erratic behaviour of this object. A series of papers reported investigations of the evolution of novae and their environment (for example, Chesneau et al., 2007) and the detection and characterisation of binaries and higher order stellar multiples. AMBER also observed the nucleus of the Seyfert galaxy NGC 3783, deriving a ring radius for the toroidal dust distribution of 0.74 milliarcseconds (Weigelt et al., 2012).

The most cited AMBER paper to date analyses the measured radii of seven low- and very-low-mass stars, finding agreement between the observed radii and the predictions of stellar evolutionary models for magnetically active low-mass stars (Demory et al., 2009; Figure 3).

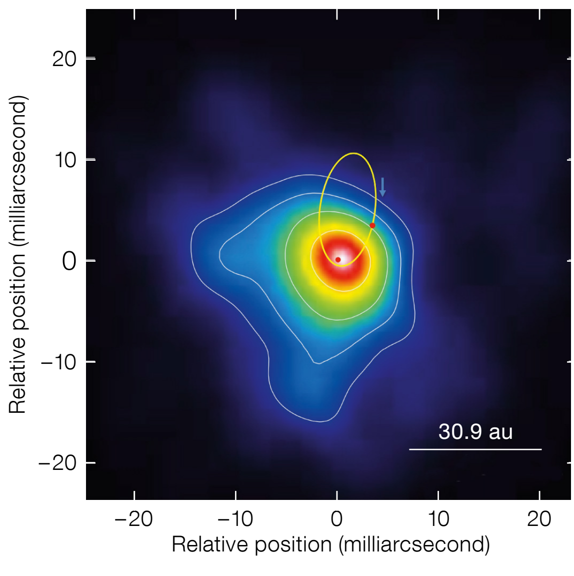


Figure 2. Aperture synthesis image of η Carinae in the Brackett γ HI transition at a radial velocity of -277 km s^{-1}. The image shows both the dense stellar wind surrounding the primary star (red, yellow, and green regions) and the fan-shaped wind-wind collision zone (blue). The image field of view is 50 × 50 milliarcseconds. Overlaid is a sketch of the orbit of the secondary star (adapted from Weigelt et al., 2016).

We note that, after the first successful science observations, an issue of Astronomy & Astrophysics (Volume 464, No. 1, March II 2007) was dedicated to the first results from AMBER, including the instrument description and the first astrophysical results.

The physics of young stars

AMBER's scientific contributions in the field of young stars are impressive. It is clear that stars accrete mass from their environments, as revealed, for example, by the spectroscopic and photometric activity of young objects. How the process of accretion actually manifests remains less clear. AMBER contributed to revealing the geometry of the accretion environment in young stars.

Notably, an aperture synthesis image created by Kraus et al. (2010) showed a disc surrounding a young, 20 $M_\odot$ star at a spatial resolution of 2.4 milliarcseconds (see Figure 4). It demonstrates the inevitability of disc formation for mass accretion to proceed, even in high-mass luminous stars. How the disc is shaped and its structure closer to the stellar surface are revealed in the 1500 visibility measurements reported by Benisty et al. (2010) where the inner few astronomical units dominate the emission in the *H*- and *K*-bands. These hot disc regions give rise to large-scale ionised winds (for example, Malbet et al., 2007), or they diminish to very compact ionised regions possibly identifying the actual process of depositing material on the star's surface or the jet launching environment (Kraus et al., 2008). The brightness, relative proximity and complexity of various physical processes operating during the accretion process make bright young stars extremely suitable targets for spectro-interferometry. These and other high-angular-resolution findings formed the rationale for the second conference dedicated to intermediate-mass pre-main-sequence stars organised in Vitacura in 2014 (de Wit et al., 2014).

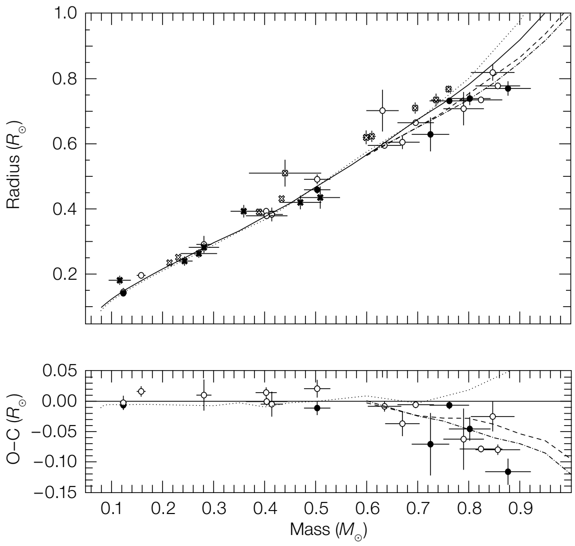
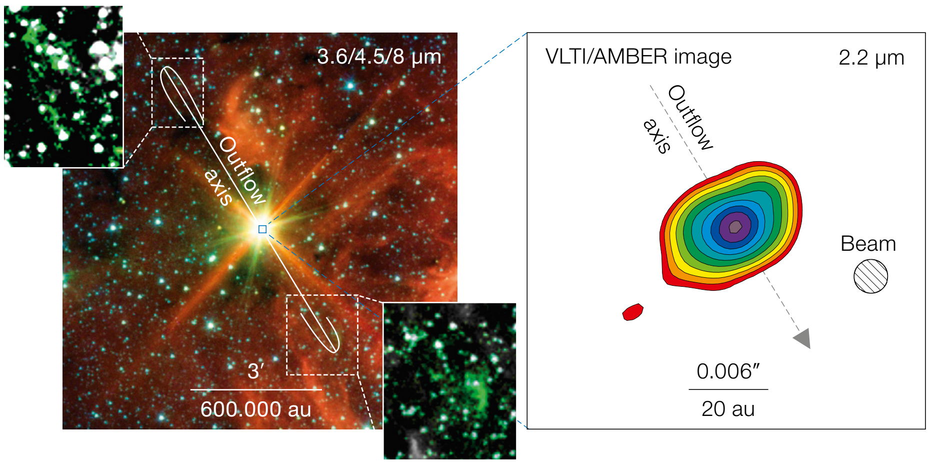


Figure 3. The mass-radius relationship for M- and K-type dwarfs, for which radii have been obtained via direct measurements with AMBER and VINCI (filled circles). Other long-baseline observations are overplotted (solid, dashed and dotted lines) in open circles. Evolutionary predictions are for an age of 5 Gyr and different values for the convective overshoot parameter (adapted from Demory et al., 2009).

Figure 4 (below). Left: Mid-infrared Spitzer composite image (3 × 3 arcminutes) of the surroundings of the 20 $M_\odot$ young star IRAS+13481-6124, revealing the outflow from the star as indicated. Right: AMBER aperture synthesis image zooming in on the accretion disc. Modelling shows that the disc has a dust-free region inside 9.5 astronomical units from the star. The structure is oriented perpendicular to the outflow direction (adapted from Kraus et al., 2010).



Fast rotating stars

The fastest rotating stars reaching critical velocity (at which a star breaks up) are the 6 to 15 $M_\odot$ stars. Indeed, the early B-type stars, as a general group, display the fastest rotation of all stars. Such rapid rotation can be assessed by either measuring the shape of the star (via visibilities), or exploiting Doppler effects in a spectral transition resulting from the stellar rotation. In the latter case, one exploits the fact that the photocentre of the stellar surface in the approaching part of the spectral line profile is different from that in the receding part. AMBER allows this effect to be measured as it provides access to the phase changes relative to each spectral bin.

Domiciano de Souza et al. (2012) infer the equatorial radius, the inclination angle and an equatorial rotational velocity of 298 +/– 9 km/s for the rapidly rotating B star Achernar using this technique (see Figure 5). Owing to this fast rotation, the classical Be stars are capable of launching stellar material into a circumstellar disc. With the help of AMBER data, direct evidence was obtained that these discs are in clear Keplerian rotation, a suggestion that dates back to their discovery in 1866 (Meilland et al., 2007). Further investigation shows that this type of disc is generally expanding, and forms a one-armed spiral density pattern that precesses with a period of a few years (Carciofi et al., 2009).

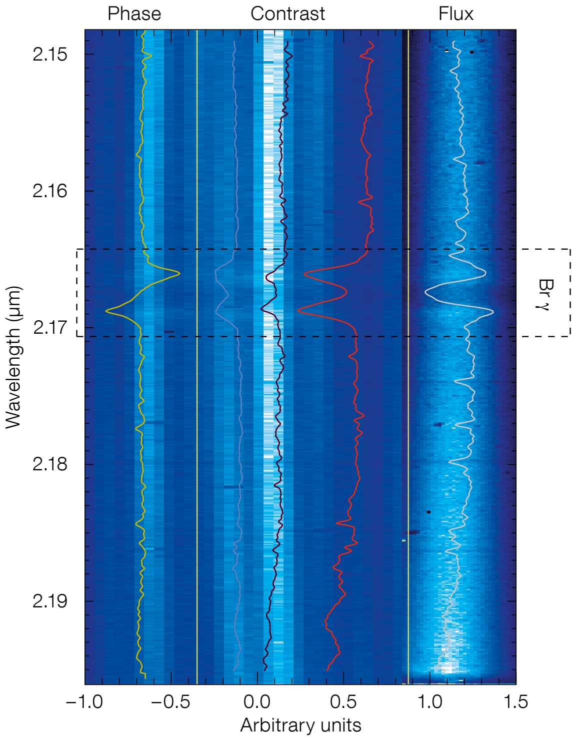


Figure 5. A popular transition is the Brackett γ H I atomic line at 2.17 μm. For the last AMBER fringes, the rapidly rotating star Achernar (αEridani) was targeted. Its rotation (~ 90% of the critical velocity) causes its equatorial diameter to be about 35% larger than its polar diameter. The blue background image shows the interferometric beam with fringes (stretching from $x = -1.0$ to 0.9), and overlayed are the extracted contrast for the three baselines and the closure phase. The image also shows one photometric beam ($x = 0.9$ to 1.5), and overlaid is Achnernar's flux spectrum. AMBER observations are sensitive to the disc rotating in the Brackett γ H I transition, characterised by a decrease in contrast and the opposite phase signature.

Cool evolved stars and their further evolution

The AMBER instrument made significant contributions to the study of cool evolved stars and their further evolution throughout its operational lifetime. In total, about a quarter of the papers based on AMBER data fall into this scientific category.

Cool evolved stars comprise AGB and red supergiant (RSG) stars, which are located on the Hertzsprung-Russell-Diagram (HRD) at effective temperatures between about 2500 and 4500 K. They cover a large range of luminosities depending on their initial mass, where AGB stars are low- to intermediate-mass stars, and RSGs their massive and high-luminosity counterparts. Owing to the low temperatures of AGB and RSG stars, molecules and dust can form in their atmospheres, and they are subsequently expelled into the interstellar medium via a stellar wind with similar mass-loss rates found in AGBs and RSGs. When AGB stars have lost a significant fraction of their mass, they evolve again toward higher effective temperatures, and via a post-AGB phase they transition to planetary nebulae. RSG stars explode as core-collapse supernovae or transition to hotter Wolf-Rayet stars, depending on their mass.

Previous interferometric observations of cool evolved stars were usually made via broad filters or sequentially in a few narrow bandpasses, the latter a time-consuming technique. AMBER has been unique in providing detailed measurements of individual lines, in particular the individual CO first overtone lines near 2.3 μm, with a high spectral resolution of R ~ 12 000 (for example, Ohnaka et al., 2011), or measurements across the full K-band with the medium spectral resolution of R ~ 1500 (for example, Wittkowski et al., 2008). Cool evolved stars appear to be extended in bandpasses that are dominated by molecular layers, and much more compact in near-continuum bands. Observing spectral channels across the K-band at once has been an essential tool to constrain dynamic model atmospheres. High-spectral-resolution studies of CO first overtone lines showed extended CO layers in detail as well as their vigorous, inhomogeneous large-scale motions.

For Mira-variable AGB stars, it has been shown that pulsation and convection can lead to strongly extended molecular atmospheres, where the temperature is cool enough for dust to form. AMBER observations of these stars have been shown to be largely consistent with dynamic model atmospheres at individual phases, and have confirmed time variability of molecular extensions on time scales of weeks to months.

For RSGs, it has been speculated that the same processes may explain their mass loss as well. However, AMBER observations of RSGs showed extensions that are larger than expected based on current dynamic model atmospheres. Direct comparisons of AMBER data with 1D and 3D dynamic model atmospheres showed that current models of RSGs based on pulsation and convection alone cannot explain observed extensions of RSG atmospheres, and cannot explain how the atmosphere is extended to radii where dust can form (for example, Arroyo-Torres et al., 2015). This points to missing physical processes in current RSG dynamic models — an unsolved problem that is a heritage of AMBER and that is due to be investigated further by the next-generation interferometric instruments. AMBER has also provided observations of non-Mira red giants which are partly consistent with hydrostatic models and partly show discrepancies with models similar to RSGs. AMBER has provided image reconstructions of both the extended atmospheres of AGB stars (for example, Le Bouquin et al., 2009) and RSGs (for example, Ohnaka, Weigelt & Hofmann, 2017; see Figure 6).

Conclusion

On the night of 3 September 2018, the interferometric instrument AMBER observed its last fringes. After serving the European astronomy community for over thirteen years, the instrument was decommissioned during the course of the interventions in the VLTI laboratory that were necessitated by the arrival of the adaptive optics system for the ATs (NAOMI) and the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE). AMBER operations encouraged the development of the FINITO fringe-tracker to beat the atmosphere's phase disturbance, which enabled longer detector integration times. With the

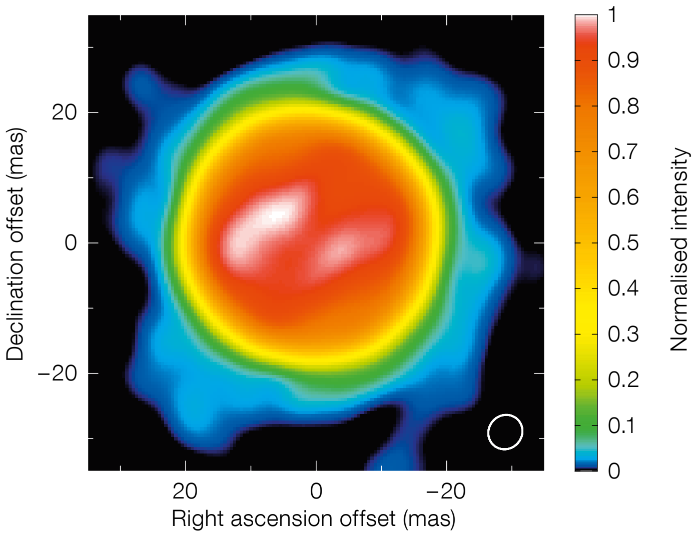


Figure 6. Velocity-resolved aperture synthesis imaging of the red supergiant Antares. This monochromatic image was obtained at the centre of the CO transition at 2.30665 μm. AMBER's high spatial and spectral resolution allowed the observations to measure the "vigorous" motion above the complex red supergiant photosphere (adapted from Ohnaka, Weigelt & Hofmann, 2017).

decommissioning of both AMBER and FINITO, the VLT Interferometer bids farewell to the era of the first generation of interferometric instruments at Paranal. The new era of VLTI operations is marked by routinely making use of the four-telescope combiner instruments, GRAVITY, PIONIER, and the latest addition, MATISSE.

In many respects, AMBER represented a breakthrough in optical interferometry. At Paranal, it was the first instrument to combine the beams of three telescopes, providing access to the all-important closure phase, without which it is not possible to reconstruct images of celestial objects from interferometric observations. As such, and in addition to the visibility and phase studies, AMBER has delivered a great number of images at milliarcsecond scales, providing new insights into astrophysical areas that could not be spatially resolved with single optical telescopes (see Figures 2, 4, 6). The second generation of VLTI instruments has inherited and profited from the lessons learned, and the VLTI upgrade started in 2015 is providing a further enhanced facility (Woillez et al., 2015). The performance demonstrated today by GRAVITY shows that the initial goals set by AMBER were not unrealistic.

Part of AMBER's legacy is the novel way in which interferometric observables are extracted from the data, how fringe patterns are initially recorded. Another innovation is the pixel-to-visibility matrix (P2VM) method implemented in the instrument's design. Originally invented for AMBER, this method has found its way into PIONIER and GRAVITY instruments.

Furthermore, AMBER was the first instrument for which real time fringe-tracking data were used to enhance the data reduction. This is routinely done for GRAVITY, and will likely be done for MATISSE. The latter instrument also inherited the fringe combination scheme employed by AMBER. Finally, the unique aspect of the AMBER instrument was its spectral resolution, which initiated the technique of spectro-interferometry. With a resolving power of 12 000, AMBER was able to spectrally and spatially resolve the dynamics of circumstellar phenomena, and paved the way for GRAVITY and MATISSE operations. The literature will no doubt continue to see numerous science papers originating from AMBER data in the coming years.

Acknowledgements

A large consortium of institutes, scientists and engineers contributed to AMBER. A list of the AMBER consortium members is included in this article[1]. We thank Armando Domiciano de Souza and Thomas Rivinius for useful discussions regarding classical Be stars.

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Links

[1] List of AMBER consortium members: http://amber.obs.ujf-grenoble.fr/spipe703.html

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Modelling Data in CASA

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The Common Astronomy Software Applications (CASA) package provides a powerful tool for post-processing Atacama Large Millimeter/submillimeter Array (ALMA) and Karl G. Jansky Very Large Array (VLA) observations, but contains only rudimentary functions for modelling the data. In order to derive physical parameters as well as information on the location and the kinematics of the emitting gas, modelling of the observed data is inescapable. Such modelling can take the form of inference — where physical parameters are inferred from the data — or forward modelling — where model calculations are used to produce synthetic observations for comparison with data. We present two interfaces that allow the use of modelling tools for both flavours from within CASA: the eXtended CASA Line Analysis Sofware Suite (XCLASS); and Adaptable Radiative Transfer Innovations for Submillimeter Telescopes (ARTIST).

XCLASS

XCLASS[1] (Möller, Endres & Schilke, 2017) is a full message passing interface (MPI) parallelised toolbox for CASA (McMullin, et al., 2007), providing new functions for modelling interferometric and single-dish data. It produces physical parameter fits for all molecules in a dataset. This also allows line identification, but also provides much more information.

In contrast to many other radiative transfer programmes, XCLASS always takes all lines of a species in a given frequency range into account, which reduces the risk of misassignment as a result of blends, and allows for the robust identification of species. In order to derive physical parameters, XCLASS models a spectrum by solving the radiative transfer equation for an isothermal object in one dimension (called a detection equation) assuming local thermodynamic equilibrium (LTE). XCLASS is designed to describe line-rich sources which often have high densities, so LTE is a reasonable approximation. Additionally, a non-LTE (NLTE) description requires collision rates which are only available for a few molecules. Molecular data required by XCLASS are taken from an embedded SQLite3 database containing entries from the Cologne Database for Molecular Spectroscopy[2] (CDMS; Endres et al., 2016, Müller et al., 2005) and NASA Jet Propulsion Laboratory[3] (JPL; Pickett et al., 1998) using the Virtual Atomic and Molecular Data Centre[4] (VAMDC) portal.

XCLASS is able to model a spectrum with an arbitrary number of molecules, where the contribution of each molecule is described by an arbitrary number of components (see Figure 1). Components can be identified as spatially distinct sources such as clumps, hot dense cores, colder envelopes or outflows, and can usually be distinguished by different radial velocities. They do not interact with each other radiatively but are superimposed in the model. Each component is described by the source size, the temperature, the column density, and the velocity width and offset, all of which have to be defined by the user in an input file. The Splatalogue[a] syntax for molecule names can also be employed, to provide compatibility with the rest of CASA.

MAGIX

Owing to the large number of input parameters required by XCLASS, it is essential to use a powerful MPI parallelised optimisation package to achieve a good description of the observational data. Therefore, XCLASS contains the MAGIX package[5] (Möller et al., 2013), which is a model optimiser that provides an interface between existing codes and an iteration engine. The package attempts to minimise deviations of the model results from observational data using a variety of algorithms, including swarm algorithms to find global minima, thereby constraining the values of the model parameters and providing corresponding error estimates. Many other model programmes can be combined with MAGIX to explore their parameter space and find the set of parameter values that best fits observational data.

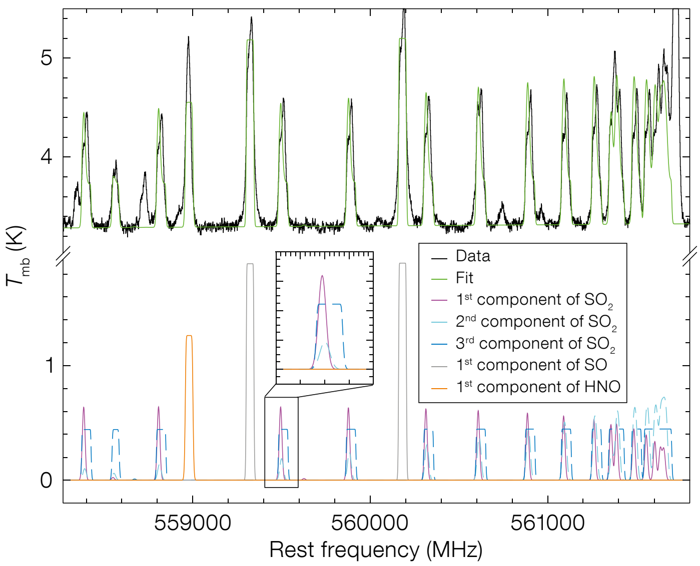

Figure 1. The myCLASS function was used to model HIFI data of Sgr B2(M) (black) using SO_2 (with three different components), SO (with one component), and HNO (with one component). The intensities of each component are shown in the bottom half (Möller et al., 2013).

New functions for CASA

XCLASS provides, among other things, two functions (myXCLASSFit and myXCLASSMapFit) for CASA, which provide the option of fitting the input parameters to observational data. The myXCLASSFit function can be used to fit single spectra, i.e., to fit multiple frequency ranges simultaneously in multiple files, and it returns the optimised input file and the corresponding modelled spectra.

In addition to that, the XCLASS interface contains the myXCLASSMapFit function, which fits one or more complete (FITS) data cubes. For this, the myXCLASSMapFit function reads in the data cube(s), extracts the spectra for each pixel and fits each of these spectra separately. It offers the possibility of limiting the fit to certain frequency ranges of a spectrum and to a user defined region of the cube(s). At the end of the whole fitting procedure, the myXCLASSMapFit function creates FITS images for each free parameter of the best fit, where each pixel corresponds to the value of the optimised parameter taken from the best fit for that pixel (see Figure 2). Furthermore, the myXCLASSMapFit function creates FITS cubes for each fitted data cube, where each pixel contains the modelled spectrum.

Some applications of this include temperature maps, as well as first and second moment maps, which are based on the simultaneous fitting of many lines, and are fairly robust against line confusion and blending of single lines — this can be a severe issue in many ALMA datasets with line-rich sources.

Finally, XCLASS provides an automatic line identification function to identify species in the given spectra. The automatic line identification (LineID) function consists of two parts. The function starts by determining all molecules that have at least one transition within the user-defined frequency range(s). The LineID function then performs single molecule fits to calculate the contribution of each molecule. If a molecule covers a defined fraction of the spectrum the molecule is provisionally identified and the corresponding optimised input file is appended to a so-called overall input file, which

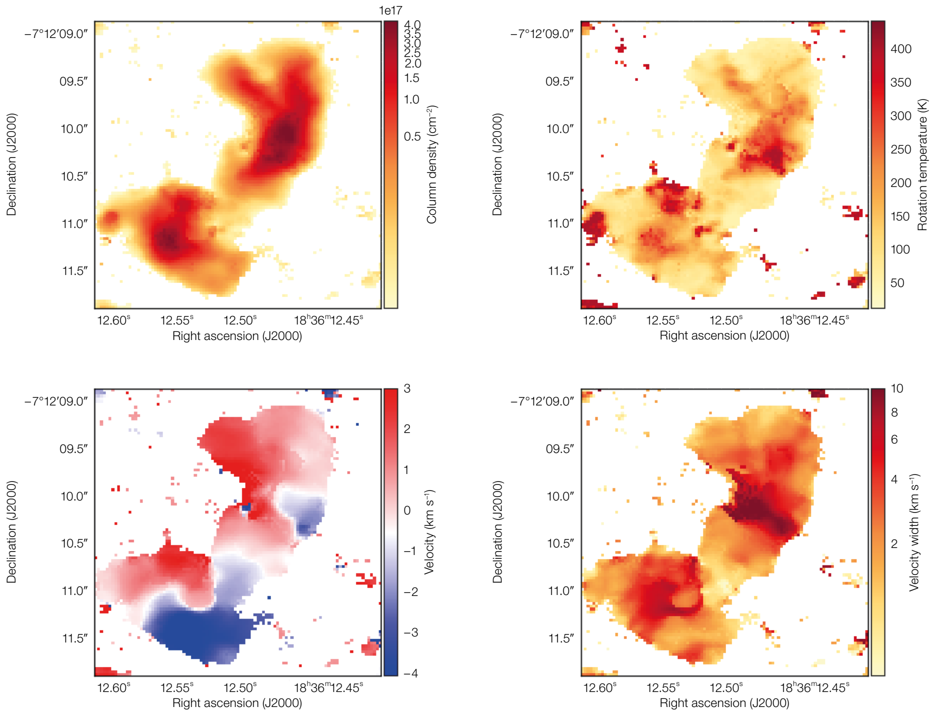

Figure 2. Example of parameter maps created by the myXCLASSMapFit function using nine transitions of CH_3OCHO simultaneously, taken from an ALMA dataset of the core of G24.78 (Moscadelli et al., 2018).

describes the contribution of all of the identified molecules. After all single molecule fits are completed, the LineID function performs a final (global) fit, using the aforementioned overall input file to account for line blending effects.

ARTIST

The ARTIST[6] software was developed with the aim of providing an easy entry-level modelling suite for star formation and asymptotic giant branch (AGB) studies with submillimetre telescopes (Padovani et al., 2012). It represents a different approach to source modelling than the one described above. In this one, the user starts with a description of the astrophysical object in question and produces observables for comparison with actual data or as predictions for ALMA proposals. ARTIST combines nine pre-defined, parametrised descriptions of models of star-forming cores and circumstellar disks with a NLTE molecular excitation tool (LIne Modelling Engine [LIME][7]; Brinch & Hogerheijde, 2010). It takes molecular collision rates from the Leiden Atomic and Molecular (LAMDA) database[8] (Schöier et al., 2005) and it outputs FITS cubes of the molecular line emission. These FITS cubes can then be further processed, for example using CASA to simulate the response of a single-dish telescope or interferometric array.

In its original form, ARTIST employed a graphical user interface to set the model parameters. The new release of ARTIST allows users to set the model parameters directly from the CASA command interface, in the same keyword-driven fashion as other CASA tools, to enable new users to start exploring realistic astrophysical models more easily. It does this by providing two CASA tasks called limesolver and raytrace.

The source models in ARTIST

ARTIST contains nine popular astrophysical models: the Bonnor-Ebert sphere (Ebert, 1955; Bonnor, 1956); self-similar collapse of an isothermal sphere (Shu, 1977); models of collapsing and rotating or magnetised cloud cores (Ulrich, 1976; Li & Shu, 1996; Allen, Li & Shu, 2003; Mendoza, Tejeda & Nagel, 2009);

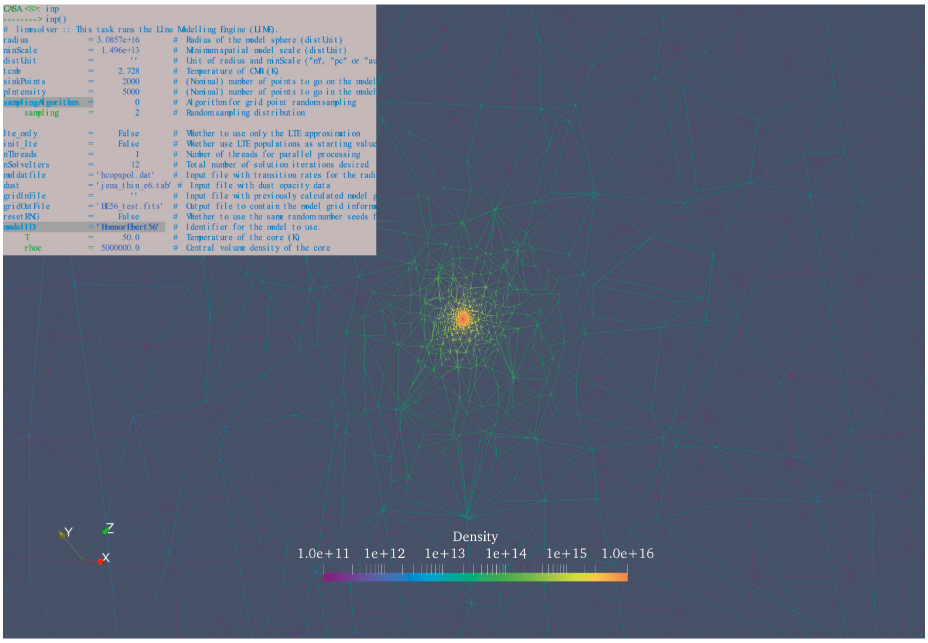

Figure 3. Screen shot of the ARTIST CASA task limesolver with a model setup for a Bonnor-Ebert sphere. In the background, the resulting LIME grid is shown.

protoplanetary discs (Chiang & Goldreich, 1997; Dullemond, Dominik & Natta, 2001); and the circumstellar envelopes of evolved stars (Mamon, Glassgold & Huggins, 1988). In addition to these pre-defined models, specification of physical models by tabulated data is possible. The CASA task limesolver allows the user to select the source model and set its parameters. An example of setting the source model parameters through CASA keywords in given in Figure 3.

The molecular excitation and radiation transfer inside ARTIST: LIME

Within limesolver, the user also provides the necessary information to solve the molecular excitation. To do this, ARTIST uses the LIME code. LIME is a versatile NLTE-accelerated Monte Carlo code that employs flexible gridding (Brinch & Hogerheijde, 2010), and comes packaged with ARTIST. The information that LIME needs includes the molecule of interest, the collision rate file from the LAMBDA database, any dust properties, the number of grid points and iterations, and whether LTE or NLTE calculations are requested. Once all of these are defined, the calculation starts. The progress of LIME can be monitored via the CASA logger just like any other CASA task. Depending on the size of the grid, the number of energy levels of the molecule, and whether LTE (fast) or NLTE (slower) is requested, the time it takes for the calculation to finish varies between a few minutes to many hours on typical high-end CPUs. The calculation is parallelised and can be run on multiple cores. On completion, LIME will write a file with the molecular excitation at each grid point, and return the CASA prompt.

Post-processing the ARTIST FITS cubes

The next step in the simulation is provided by the ARTIST CASA task raytrace, which calculates the emission on the sky for a chosen distance to the object and viewing orientation. The user sets the pixel size, field of view, spectral resolution and number of spectral channels, as well as the molecular transition of interest. Typical run times are of the order of a few minutes for a full FITS cube.

The resulting FITS cube is fully compliant with CASA, and can be used as input for further processing. Figure 4 shows the results of a calculation of a Bonnor-Ebert sphere, after running the FITS output through simobserve. The resulting image cube can be compared to actual ALMA observations to judge the similarity of the model to the data, or it can be used to make predictions for ALMA proposals.

It is important to remember that the models included in ARTIST are not fully self-contained. Some models include both a density and a temperature structure; others may only include a density

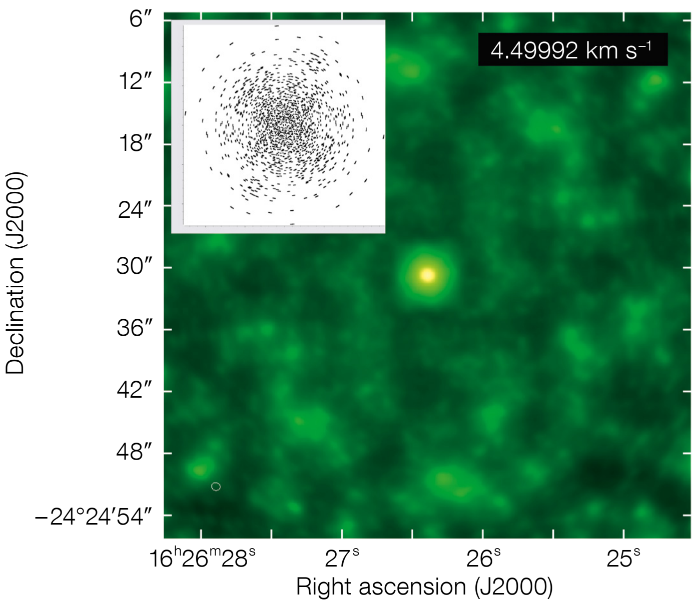

Figure 4. Output from the ARTIST CASA tasks limesolver and raytrace, after postprocessing through simobserve. The inset shows the (*u*, *v*) coverage. The model is the same as in Figure 3; a Bonnor-Ebert sphere, and a single velocity channel is shown.

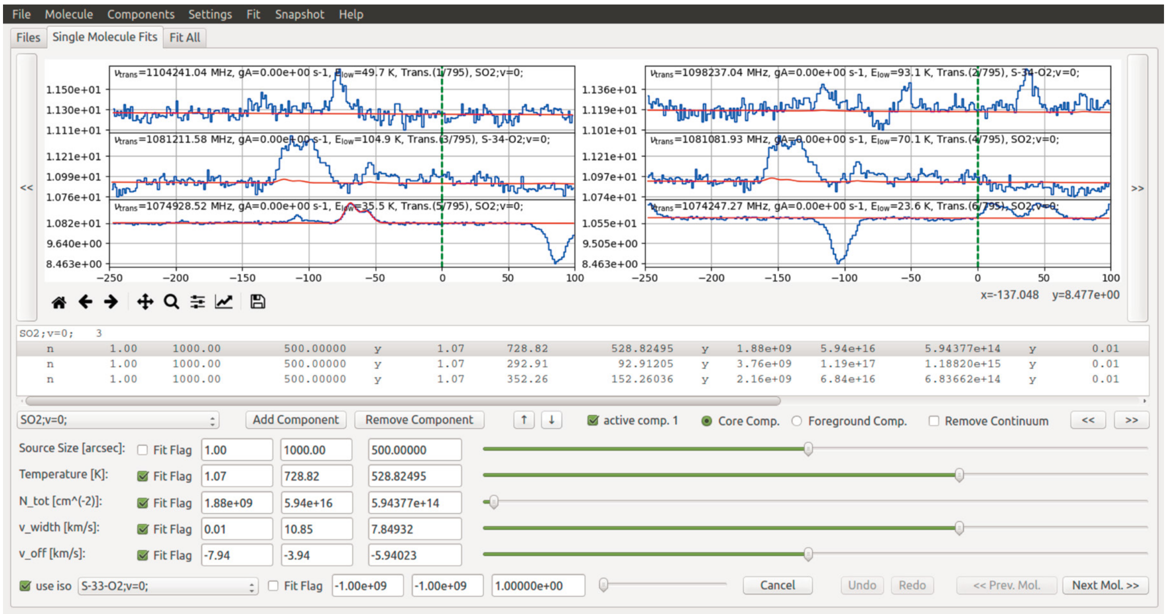

Figure 5. Currently developed user-friendly XCLASS GUI.

structure, leaving it to the user to provide a simple parameterised temperature field. However, the code does not check if this temperature field is consistent with the luminosity of any central star and the density structure of the source. ARTIST does not aim to provide such complete source modelling. Instead, ARTIST aims to provide easy access to popular models that allow users to quickly explore ALMA observables. Further, more detailed modelling requires more realistic source models and the use of the stand-alone LIME package. However, ARTIST would be the code of choice for users who want to quickly obtain a rough indication of the observables.

Outlook

In one of the next XCLASS releases, we will include a user-friendly graphical user interface (GUI), which is currently under development (see Figure 5 for a prototype), to lower the threshold of training required for new users of XCLASS. Additionally, we are working on several extensions, including NLTE, radio recombination lines, (in LTE and NLTE), non-thermal continuum, non-Gaussian line shapes (Lorentz, Voigt and Horn), local overlap of neighbouring lines, and a better source description. Furthermore, we will include a new XCLASS function called CubeFit, which offers the possibility of describing a data cube using a physical model, and fitting the model parameters. Further developments for the LIME radiation transfer engine inside ARTIST will be implemented as they become available. Additional astrophysical models will be included in ARTIST, and we encourage users to make suggestions about which models are the most useful for their research.

Acknowledgements

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Links

[1] XCLASS software including a manual is available at: https://xclass.astro.uni-koeln.de/
[2] Cologne Database for Molecular Spectroscopy (CDMS): http://www.cdms.de
[3] Molecular spectroscopy at JPL: http://spec.jpl.nasa.gov
[4] Virtual Atomic and Molecular Data Centre: http://www.vamdc.eu
[5] The MAGIX package can be downloaded from https://magix.astro.uni-koeln.de
[6] The ARTIST package can be found at: http://www.alma-allegro.nl/artist/
[7] LIME: http://github.com/lime-rt/lime
[8] LAMDA: http://www.strw.leidenuniv.nl/~moldata

Notes

[a] The name splatalogue is derived from "spectral line catalogue" and is a database for astronomical spectroscopy that contains information on nearly six million spectral lines.




First light images from the four SPECULOOS telescopes. Clockwise from top left: Centaurus A (Io), Eta Carinae (Europa), Horsehead Nebula (Callisto), NGC 6902 (Ganymede).

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ALMA Observations of the Epoch of Planet Formation

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Planetary systems form in the discs of gas and dust that orbit young stars. In the past few years, observations of these discs at (sub-)millimetre wavelengths with very fine angular resolution have started to uncover the hallmarks of small-scale substructures in the spatial distributions of their pebble-sized particles. These are some of the fundamental signatures of the planet formation epoch, since they trace localised concentrations of material that facilitate the formation of much larger planetary building blocks, and may themselves be created by young planets interacting with their birth environments.

Circumstellar discs and planet formation

The effort to understand our origins, and therefore to add some existential context to our place in the universe, is a fundamental component of astrophysics research. This more philosophical aspect of the field takes on a starkly practical tone for the specialised topic of planets. In less than three decades, the planetary science landscape has been completely transformed, going from the modest membership of our lonely Solar System to a galaxy that is literally teeming with exoplanets. Astronomical observations of this abundance of other worlds have guided theoretical studies that aim to explain the key physical properties of the exoplanet population. One crucial outcome of all that work is the realisation that many of the most basic planetary characteristics (masses, orbits, atmospheric compositions, etc.) are imprinted around the time a planet is formed. This implies that key aspects of planetary systems hinge on complex interactions with their birth environment — specifically, remnant material in the discs that orbit young stars.

The origins of the Solar System have long been associated with a progenitor disc structure, thanks to the recognition that the planets orbit the Sun in the same direction and confined to the relatively narrow ecliptic plane. But the connection between stars and discs is both more general and more fundamental. Circumstellar discs are the natural consequences of angular momentum conservation during the star formation process. They are created when a rotating overdensity in a molecular cloud collapses under its own gravity, which channels material into a rotationally-supported flattened morphology that both feeds mass onto the central star and, roughly a million years later, transforms into a planetary system.

It is not an exaggeration to claim that the relatively brief life of a disc both shapes and fundamentally links the properties of a star and its associated planets. In that sense, measurements of the properties of these discs are invaluable because they provide unique insights that help us build a more robust theory of star and planet formation. Over just the past few years, the disc community has focused intently on several interrelated issues that lie at the heart of the planet formation process. Below we highlight these studies in the context of a new, expansive survey of discs at very high angular resolution with the Atacama Large Millimeter/submillimeter Array (ALMA). First, we emphasise why the evolution of solids in discs is so fundamental for planet formation. Next, we explain how that evolution (and the key observables) is thought to be controlled largely by interactions with fine-scale structures in the gas disc. Then we discuss what new observations are revealing about these issues in the contexts of both disc evolution and planet formation.

The evolution of disc solids

That disc solids are important for planet formation might seem obvious. Most of the known exoplanets are small and presumed to be rocky, and even the gas giants in our Solar System are known to have massive solid cores. But making this connection requires faith in a growth process on remarkable scales; in only a few million years, the sub-micron-sized dust grains that are incorporated into a disc when it forms must increase by at least 10 orders of magnitude in size (roughly 30 orders of magnitude in mass) through a sequence of collisional agglomerations, to become a population of km-scale "planetesimal" building blocks. At that point, gravity aids their subsequent evolution to terrestrial planets or giant planet cores. In the standard theory, making planetesimals is the biggest hurdle in the planet formation process. In fact, the problems start early, with growth bottlenecks at "pebble" (mm/cm) size scales.

All of the standard planet formation models assume that the gas disc is smooth, such that its pressure decreases monotonically with distance from the host star. The corresponding radial pressure gradient imposes a small outward force on a parcel of gas, slowing its orbital speed below the Keplerian velocity. That velocity difference between the gas and the solids embedded in it is small, on the order of 1%, but it has dramatic implications for their mutual interactions. At a given location (set of physical conditions), solid particles with a specific range of sizes start to decouple from the gas flow. Those particles then feel the sub-Keplerian velocity of the gas as an aerodynamic drag force that saps their angular momentum and sends them spiralling inwards towards the global pressure maximum in the inner disc (Weidenschilling, 1977).

This migration of solids, termed radial drift, introduces two important problems. First, it enhances the relative velocities between particles, leading to destructive collisions (fragmentation). Second, and more important, because the drift timescale is much shorter than the typical collision (growth) timescale, the corresponding depletion of drifting particles effectively limits further growth (for example, Takeuchi & Lin, 2002). In the big picture, this depletion of the solids implies that planetesimal formation is inhibited beyond roughly 10 astronomical units (au). At larger radii, representing the bulk of the disc mass, radial drift is most efficient for pebbles (which achieve migration speeds on the order of 1 au per orbital period). The result is a pronounced radial size segregation of the solids; larger particles are preferentially located closer to the star. The typical disc should have its mm/cm-sized pebbles concentrated in the inner disc (for example, Birnstiel & Andrews, 2014).

In a sense it is fortunate that this migration process is so significant for pebbles, since these are the last particles in the growth sequence that are directly observable through their thermal continuum emission. Such emission is most efficient at a wavelength comparable to the particle size, making the (sub-)mm part of the spectrum the optimal tracer, and therefore ALMA the premier facility for studying this evolutionary process. Measurements of the spatial distribution of the mm "colour" (spectrum shape) provide qualitative support for the radial size segregation predicted by the standard theory for the evolution of disc solids (for example, Pérez et al., 2012). But the extended morphologies of the mm-wavelength continuum emission from many nearby discs are in clear, quantitative conflict with these predictions (for example, Tripathi et al., 2017).

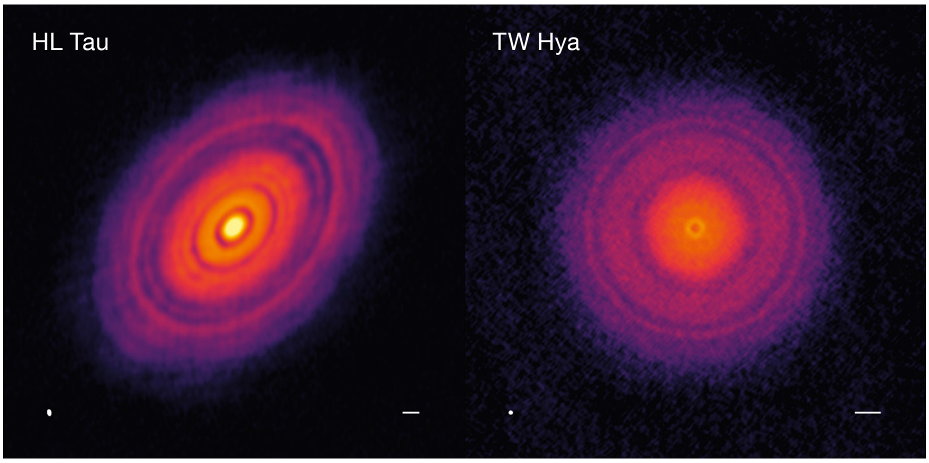


Figure 1. ALMA images of the 1-mm continuum emission from the HL Tau (ALMA Partnership et al., 2015) and TW Hya (Andrews et al., 2016) protoplanetary discs. With access to high angular resolution, a series of concentric bright rings and dark gaps on scales of a few astronomical units (au) become apparent. The scale bars mark 10 au; the synthesised beam (resolution element) is shown as an ellipse in the lower left corner of each image.

In short, resolved observations of mm-continuum emission from discs do indicate that the growth and migration of disc solids are occurring, but they also point to substantial tension with the predicted efficiency of those processes. The observed migration is less pronounced than would be expected for standard assumptions.

A solution in substructures

The most natural way to reconcile this discrepancy is to relax the standard assumptions; gas discs are probably highly structured, not smooth. At any local pressure maximum, there is no force contribution on a parcel of gas from a pressure gradient (by definition), so it will orbit at the Keplerian velocity. This eliminates the drag force on the solids, substantially prolonging the drift timescale. In effect, a local gas pressure maximum is a particle "trap"; solids will migrate toward it and then park there. In addition to solving the drift timescale problem, the associated concentration of solids (relative to gas) could trigger rapid planetesimal formation via the gravitational and/or streaming instability.

The first and clearest evidence for such particle traps came from mm continuum observations of "transition" discs, which appear as emission rings that peak tens of au from their host stars (Andrews et al., 2011; Pinilla et al., 2018). But this subset of the general disc population is rare (about 10%); it is unlikely to represent the general solution to the efficiency issues noted above. Nevertheless, the mechanism is sound; the issue is perhaps related to scales. The leading hypothesis is that the "normal" disc population is riddled with smaller gas pressure modulations with lower amplitudes — substructures — that perform the same roles in concentrating solids (Pinilla et al., 2012).

The commissioning of the highest angular resolution mode available with the ALMA interferometer brought stunning confirmation of this hypothesis. Images of the mm continuum emission from the HL Tau and TW Hya discs at roughly 30 milliarcsecond resolution, reproduced in Figure 1, revealed a series of narrow (a few au wide) ring and gap substructures (ALMA Partnership et al., 2015; Andrews et al., 2016). Evidence for similar features at coarser resolutions has also continued to percolate out from serendipitous ALMA discoveries, and is complemented by analogous features in infrared images of starlight scattered off much smaller dust grains (thereby tracing the gas) in the disc surface layers (for example, Avenhaus et al., 2018).

In a few short years, these measurements have fundamentally shifted assumptions about disc properties in a new generation of planet formation models. Much of the current focus in the field is on the origins of the observed substructures, which range from migration modulations near volatile condensation fronts, to the complex dynamical interplay between magnetic fields, gas and solids, to the gravitational interactions between disc material and very young planets. At first glance, the last option seems like a circular logic; substructures are essential to make planetesimals (and therefore planets), but then we are invoking planets as the origins of substructures. But this is not necessarily a problem; it merely implies that planetesimal (and thereby planet) formation occurs efficiently, in the earliest stages of disc evolution. If this is true, the substructures we observe are probably a second generation of features, and the underlying framework of planet formation models will see a drastic modification.

In any case, the natural next step is to learn more about the demographics of small-scale disc substructures, and to use that information to help understand their origins.

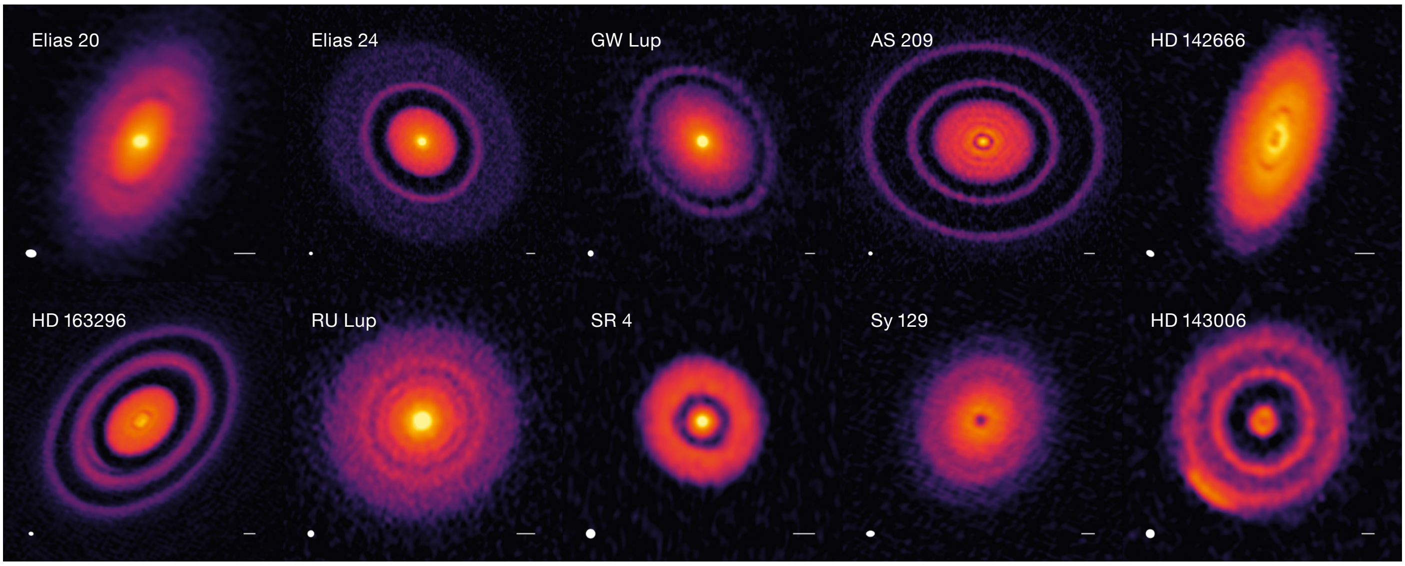
The Disc Substructures at High Angular Resolution Project (DSHARP)

To that end, our team has conducted one of the preliminary ALMA Large Programs to measure the 1.25-mm continuum emission (and CO $J = 2–1$ emission line) for 20 nearby discs at an angular resolution of 35 milliarcseconds, equivalent to around 5 au in projected spatial resolution (Andrews et al., 2018). The goals of the Disc Substructures at High Angular Resolution Project (DSHARP) are to assess the prevalence, forms, sizes, spacings, symmetry, and amplitudes of substructures, to get a preliminary look at how they might depend on the bulk disc or stellar host properties, to compare those characteristics with hypotheses for their origins, and to facilitate a community-wide effort to build on those results. This last aspect is achieved with the full DSHARP data release, including calibrated visibilities, images, scripts, and various secondary products[1].

The ALMA continuum images reveal that all discs in the DSHARP sample contain substructures indicative of localised pebble concentrations. These features are located over a wide range of disc radii (from 5 to 150 au) and exhibit a diversity of characteristic size scales (a few au to tens of au) and intensity contrasts (a few percent to roughly a factor of two). Concentric bright rings and dark gaps in the emission distribution are by far the most common forms of substructure, as illustrated in Figure 2 (Huang et al., 2018a). While simple in form, these rings and gaps have a diverse range of locations (and spacings), widths, and amplitudes; moreover, there is no clear association between their properties and any characteristics of the stellar hosts. These substructures appear to be circular (after accounting for the disc viewing angles) and azimuthally symmetric. Only two cases show obvious deviations from axisymmetry, in the form of narrow, arc-like features (Isella et al., 2018; Pérez et al., 2018). Some of the continuum morphologies can be decomposed solely into narrow rings, and occasionally additional gaps are even present in the CO line emission well beyond the radii where continuum emission is detected (Guzmán et al., 2018).

The sizes, amplitudes, and locations of many of the bright ring features are found to be consistent with theoretical predictions for particle trapping at local gas pressure maxima, with densities that are nominally high enough to facilitate rapid planetesimal formation (Dullemond et al., 2018). Alongside the fact that there is no connection between the locations or spacings of these features with the stellar host luminosities (and thereby their temperatures), there is no support for the hypothesis that volatile condensation fronts are associated with substructures in the DSHARP sample discs (Huang et al., 2018a). While some viable, though not yet quantitatively predictive, alterna-

Figure 2. A DSHARP image gallery of the 1.25-mm continuum emission from a subset of the discs that exhibit a diverse set of ring and gap substructures (Andrews et al., 2018; Huang et al., 2018a; Guzmán et al., 2018; Isella et al., 2018; Pérez et al., 2018).



tive mechanisms for producing these kinds of substructures exist, there are compelling signals that they may be produced by planet-disc interactions. Some of the substructures appear to have resonant spacings and double-gap morphologies similar to predictions from hydrodynamics simulations; the arc features noted in two cases are qualitatively similar to models of vortex trapping near giant planet perturbers, and a new suite of hydrodynamics simulations provides compelling comparisons to many of the observed continuum emission morphologies (Zhang et al., 2018). For some reasonable assumptions, those simulations suggest that the observed disc gaps are plausibly opened by planets with masses 10 to 100 times as large as the mass of the Earth and semimajor axes from roughly 10 to 100 au.

The five discs in the DSHARP sample that are not shown in Figure 2 are dominated by a different substructure morphology: a pronounced spiral pattern. The two of these shown in Figure 3 are known triple star systems (Kurtovic et al., 2018); the discs around the primaries show the clear spiral perturbations that are theoretically expected from tidal interactions in such systems. The CO data in both cases are particularly interesting, revealing clear evidence for misalignments between the disc and orbital planes as well as tidal stripping from previous encounters. The remaining three discs with spiral substructures orbit single stars; their spectacular continuum maps are shown in Figure 4 (Huang et al., 2018b). Each of these discs has a symmetric two-armed morphology that spans the full extent of the continuum emission. These patterns are strikingly complicated; they appear to bifurcate or merge into concentric rings, and in each case at least one circular gap is superposed on the spiral. In these systems, it seems likely that multiple mechanisms are responsible for generating the observed features. But in terms of the spiral component, it is interesting to note that these tend to be the largest, coldest discs in the DSHARP sample. That lends at least some anecdotal support to the idea that a global gravitational instability may be operating.

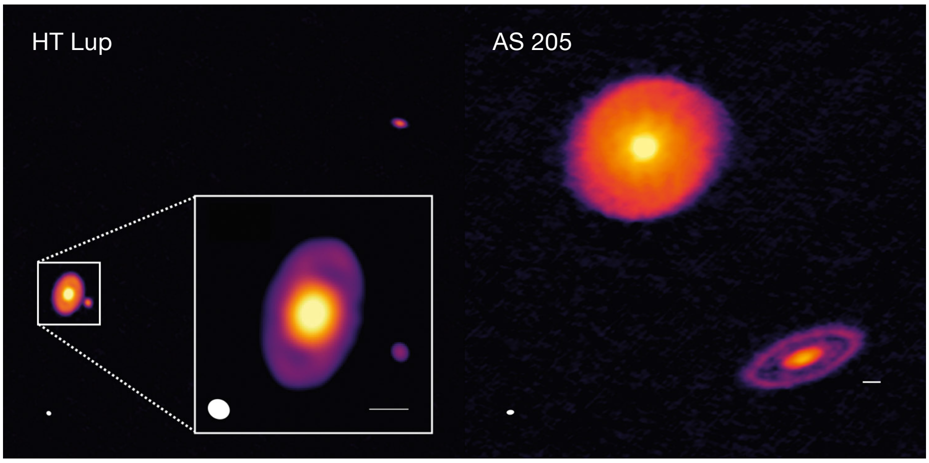


Figure 3. Images of the 1.25-mm continuum emission from discs in the two triple systems in the DSHARP sample (Kurtovic et al., 2018). Note the two-armed spiral morphologies of the discs around the primary stars, indicative of dynamical interactions between the individual components.

Closing thoughts: the start of observational planet formation studies

The DSHARP dataset and preliminary results, along with the many related studies that they build upon, herald the start of a new era in planet formation research. Where much of the effort had previously been theoretical in nature, ALMA and cutting-edge adaptive optics facilities in the infrared promise to drive rapid advances on the observational side. There are many different avenues to pursue that can better place the DSHARP results in context, including extending the sample in orthogonal directions (for example, younger discs, fainter or smaller discs), folding in complementary datasets

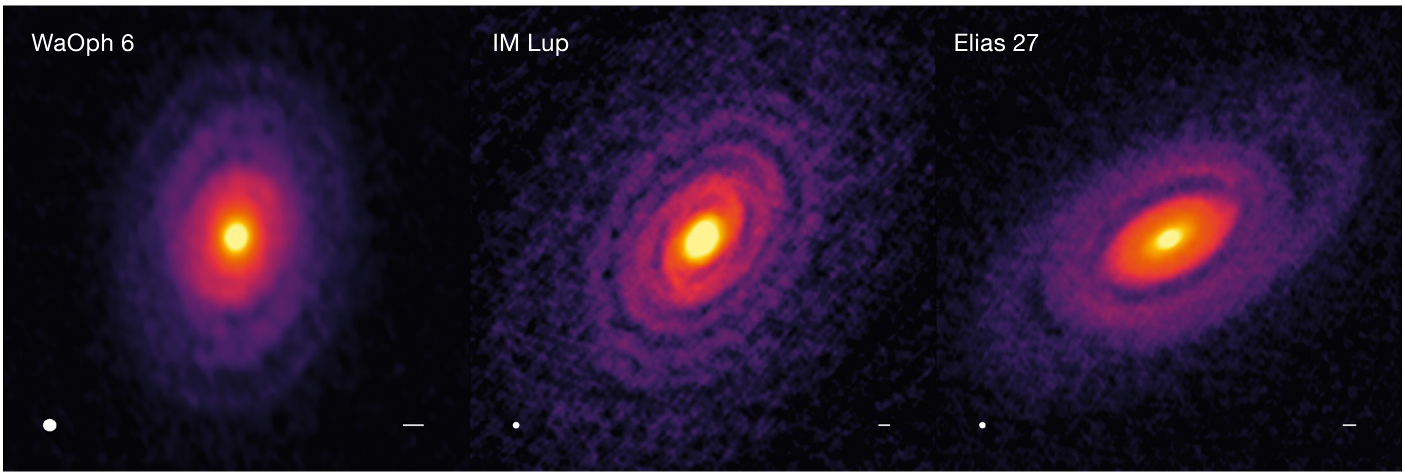


Figure 4. The striking spiral morphologies in the 1.25-mm continuum emission from a small subset of the DSHARP sample discs, in this case for single (isolated) hosts (Huang et al., 2018b). The spiral patterns are complex and superposed with circular features.

(continuum measurements at a longer wavelength to explore the particle trap properties, molecular spectral line or scattered light images to look for related gas signatures, etc.), and undertaking more detailed modelling of individual targets to directly confront theoretical predictions. In any case, ALMA is proving to be a transformational tool. The early results using ALMA data described here should serve as launching points that mark a productive shift in the field, where new data and analyses push towards a new model that robustly connects the growth and migration of disc solids to the planet formation process, and thereby the exoplanet population we observe around nearby main-sequence stars.

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Links

[1] Data Release webpage for DSHARP: https://almascience.org/alma-data/lp/DSHARP

D. Kordan/ESO

ALMA antennas are located at the Chajnantor Plateau at an altitude of 5000 metres, one of the driest places in the world.

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A First Spectroscopic Census of the Dwarf Galaxy Leo P

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A longstanding quest in studies of luminous, massive stars has been to understand the role of environment on their evolution. The abundance of metals in their atmospheres has a significant impact on their physical properties, strongly influencing the feedback they have on their surroundings and the nature of their explosive deaths. To date we have been unable to study massive stars with metallicities below 10% that of the Sun. The low oxygen abundance (3% solar) and relative proximity (~1.6 Mpc) of Leo P, a low-luminosity dwarf galaxy discovered in 2013, provides a tantalising opportunity to investigate massive stars with near-primordial compositions. Here we introduce observations of Leo P with the Multi Unit Spectroscopic Explorer (MUSE) instrument on the VLT, which have revealed its spectroscopic content for the first time.

The discovery of Leo P was reported in a series of five papers in 2013–14; the 'P' in its name refers to its pristine nature. Initially discovered from radio observations (Giovanelli et al., 2013), ground-based imaging demonstrated ongoing star formation in a luminous H II region (Rhode et al., 2014), and yielded an estimated distance of $1.72^{+0.14}_{-0.40}$ Mpc, with a stellar mass of $5.7^{+0.4}_{-1.8} \times 10^5\, M_\odot$ (McQuinn et al., 2013). Most excitingly in the context of studies of stellar populations, the estimated oxygen abundance from the auroral [O III] 4363 Å emission line from the H II region was found to be [O/H] = 7.17 ± 0.04, just 3% of solar (Skillman et al., 2013). Following its discovery, McQuinn et al. (2015) obtained exquisite imaging of Leo P with the Hubble Space Telescope (HST), providing an improved measurement of its distance (1.62 ± 0.15 Mpc), and finding that it has been making new stars at a roughly constant rate for the past 8–10 Gyr.

A relatively nearby galaxy with such a low oxygen abundance is a hugely compelling target in which to investigate the properties of high-mass stars in the very metal-deficient regime. We have model predictions for how such metal-poor stars should behave, but are unable to test these observationally with current facilities. The high-mass population of Leo P, even if relatively sparse, should provide important new insights into the stellar populations of star-forming galaxies in the early Universe, extending studies to even lower metallicities than the OB-type spectra recently identified in the Sagittarius Dwarf Irregular Galaxy (~5% solar) by Garcia (2018).

A first census of Leo P

To investigate the spectral content of Leo P we obtained service mode observations with the extended wide-field mode of MUSE on UT4 between December 2015 and March 2016. The total integration time was 6.7 hrs and the typical seeing was 0.6 arcseconds. As shown in Figure 1, the one-arcminute field of view of MUSE spans most of the visible extent of the galaxy. To extract spectra of the sources from the combined MUSE datacube we used the PampelMuse software (Kamann et al., 2013) which has been developed to recover MUSE spectra from crowded fields. For the input catalogue of sources to extract we used our photometry and astrometry of the HST images obtained with the Advanced Camera for Surveys (ACS) using the F475W and F814W filters (McQuinn et al., 2015).

The colour-magnitude diagram (CMD) of HST sources in the MUSE field is shown in Figure 2, with the points colour-coded if a first spectral classification was possible. As expected from the morphology

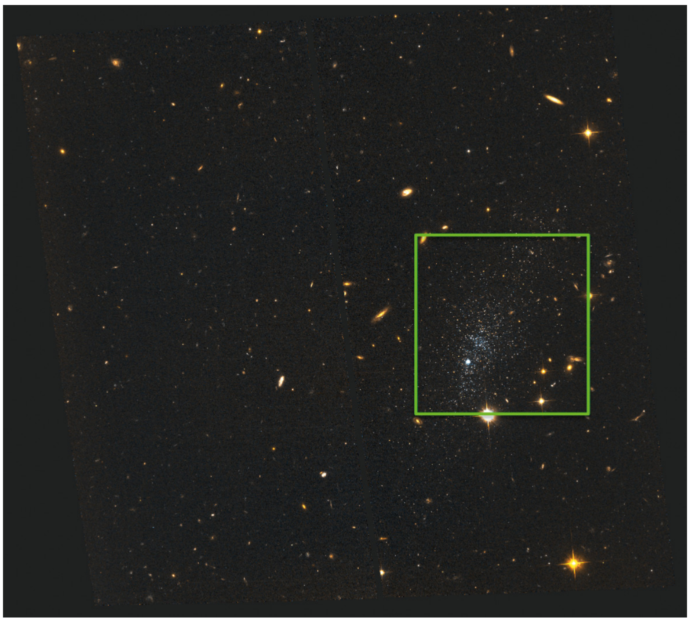

Figure 1. Observed MUSE field overlaid on the HST imaging of Leo P. The MUSE field encompasses most of the visible extent of the galaxy (north at the top, east on the left).

of the CMD we have found a number of (modestly) massive stars in the blue "plume" of the main sequence (F475W–F814W ~ 0.0 magnitudes), as well as examples of luminous, evolved cool stars above the tip of the red giant branch (RGB). In addition to these two groups, we also found a total of 20 background galaxies in the MUSE pointing, with redshifts of z = 0.36 to 2.5.

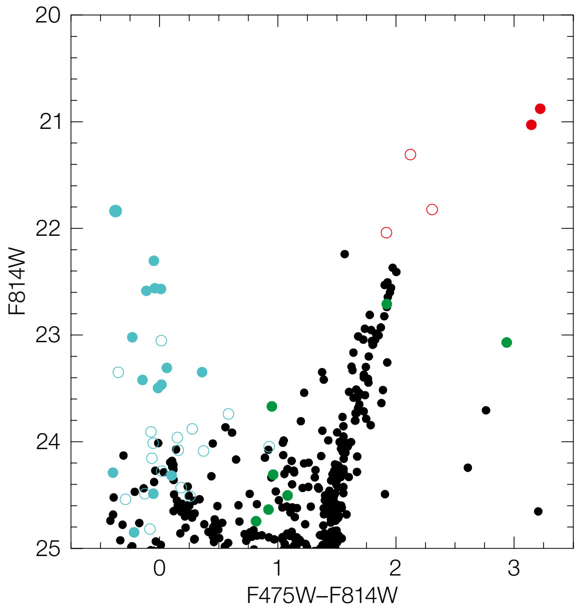

Figure 2. Colour-magnitude diagram for the MUSE field from the HST images of the region (McQuinn et al., 2015). Symbols/colours: massive stars (closed cyan circles), candidate massive stars (open cyan circles), carbon stars (closed red circles), potential AGB stars (open red circles), background galaxies (green circles).

A confirmed O-type star with $Z \sim 0.03\ Z_\odot$

The brightest blue star in the CMD is the central source in the prominent H II region. The most immediate result from the MUSE data is that this source has a clear O-type spectrum. McQuinn et al. (2015) argued from their photometry that this was a mid-to-late O-type star; now we have direct confirmation. The MUSE spectrum, part of which is shown in Figure 3, displays He II 4686 and 5411 Å absorption, necessitating the O-type classification. Unfortunately the presence of strong nebular emission (combined with the blueward limit of MUSE at ~ 4650 Å) precludes more detailed characterisation. Nonetheless, this discovery supports the argument by McQuinn et al. (2015) that the presence of such a star is contrary to models of the integrated galactic initial mass function at the low star formation rate of Leo P, where the maximum mass expected is 2.5–3 $M_\odot$ (Pflamm-Altenburg et al., 2007).

Initial classification of a further 14 early-type stars was possible via detection of Hβ absorption, combined with indications of stellar features at Hβ and steepening flux distributions toward the blue end of the spectra. From the location of these sources in Figure 2 (and taking into account the estimated distance) we suggest that most of these are B-type objects. A further 17 sources were more tentatively classified as candidates on the basis of Hβ detections. Note that the main sequence in the CMD in Figure 2 (below the O star in the H II region) extends from V ~ 22 to 25 magnitudes. Given the faintness of these targets it is really quite remarkable that we were able to (even coarsely) classify some of these objects as early-type stars from the MUSE data.

AGB stars at very low metallicity

Our original motivation for the observations was to investigate the hot stars in Leo P, but we also managed to glean some first insights into its luminous cool population thanks to the powerful capabilities of MUSE. The upper mass function of Leo P appears sufficiently sparsely populated that we did not find any red supergiant stars in the MUSE field, but we did observe five stars previously classified as candidate asymptotic giant branch (AGB) stars by Lee (2016). The strong C_2 Swan bands in the MUSE spectra in Figure 4 show that the two brightest of these (closed red symbols in Figure 2) are Carbon stars. The other three candidates were initially something of a puzzle as they were suggested by Lee as oxygen-rich M-type AGB stars, yet the MUSE spectra (one of which is shown in Figure 4) appear relatively featureless. Closer inspection reveals what appears to be absorption by the Ca II triplet (8498, 8542, 8662 Å) in the brightest of these three, with absorption also seen for the central line in the next brightest, as shown in Figure 5. The signal-to-noise of the fainter stars in the RGB in Figure 2 was too low to discern features in the individual spectra, but by co-adding

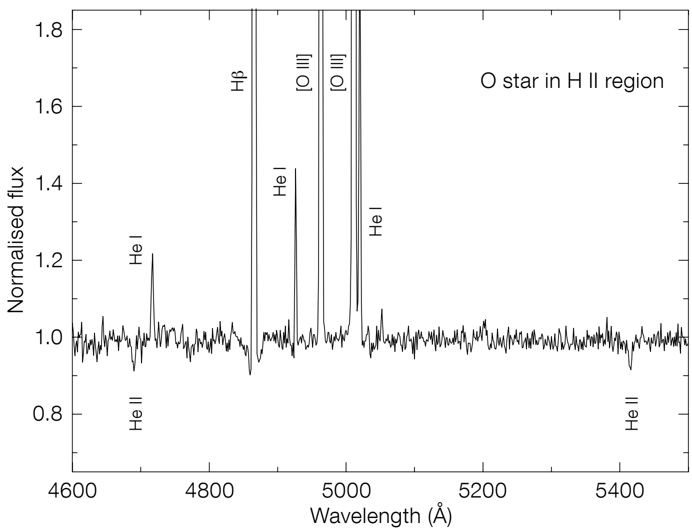

Figure 3. Blue region of the MUSE spectrum of the central source of the H II region in Leo P. The He II absorption lines (4686, 5411 Å) provide the first direct evidence for an O-type star in Leo P.

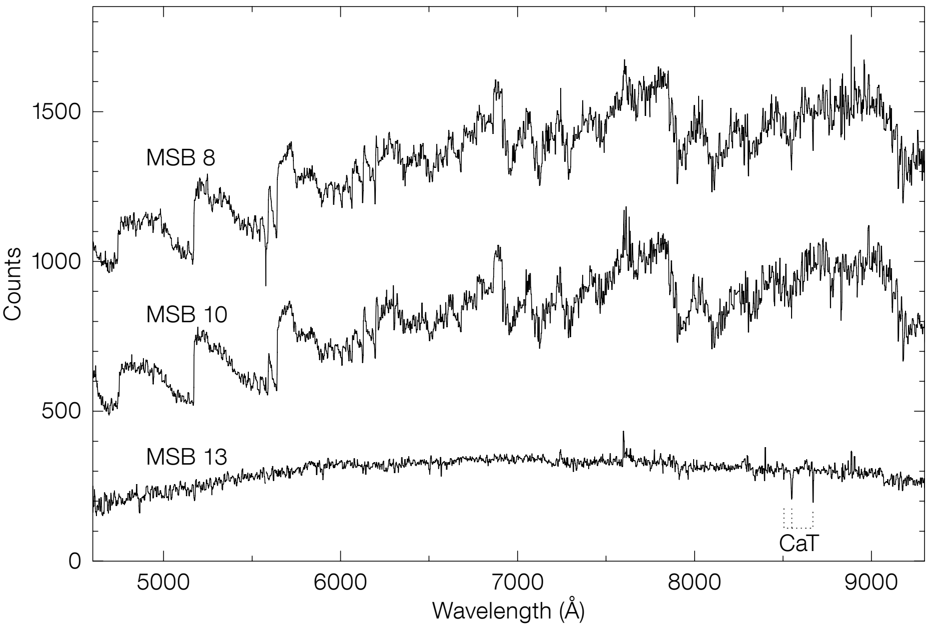

Figure 4. Spectra of three candidate asymptotic giant branch (AGB) stars in the MUSE field from Lee (2016), with identifications following McQuinn et al. (2013); each spectrum is displaced vertically by increasing multiples of 500 counts. The upper two spectra are Carbon stars. The lower spectrum is relatively featureless, but from detection of Ca II absorption and the HST photometry (Figure 2), we speculate that this and two other candidates are oxygen-rich AGB stars that are sufficiently metal poor that they do not have M-type spectra.

the spectra of the 16 sources with F814W < 23 magnitudes (excluding the five AGB candidates), we also see evidence of Ca II triplet absorption, confirming them as cool, evolved stars (lower spectrum in Figure 5).

The lack of strong molecular bands (for example, TiO) in the spectra of the candidate AGB stars is notable compared with normal M-type AGB spectra. However, we suggest that this is not unexpected given the very low metallicity, either via evolutionary effects or simply because the dearth of metallic species gives the impression of earlier-type spectra. In the context of dust production in galaxies, spectroscopic follow-up of these stars (albeit observationally demanding), would provide a significant extension to recent studies in metal-poor galaxies in the Local Group, enabling unique tests of evolutionary models.

Dramatic nebular structures

The MUSE data opened-up a third novel angle in our understanding of Leo P. Figure 6 shows the reconstructed Hα image from the MUSE datacube and reveals three new structures compared to the original discovery images, suggesting more than one site of (relatively) recent star formation. The morphology is striking, with two well-defined rings of gas emission to the north and south, and a central diffuse region. To give a sense of scale, the larger, northern Hα shell has a diameter of ~120 pc (assuming a distance of 1.62 Mpc). The absence of hot, massive stars in the region of the northern shell suggests this is an older formation (for example, a supernova remnant), rather than a large wind-blown bubble. In contrast, there are several hot stars that appear to be associated with the southern ring, with the H II region on its northern edge, suggesting an evolutionary connection.

Summary

The multiplex power of MUSE has provided the community with a fantastic instrument with which to undertake unbiased searches of the massive-star populations of galaxies in the Local Group and beyond. Studies until now have necessarily selected spectroscopic targets via photometric criteria (thus affected by interstellar reddening) and/or have targeted the most active star-forming regions of external galaxies. Leo P is an excellent example of the second point, where we have found a number of massive stars tens of parsecs away from the main H II region that we most likely would not have targeted otherwise. A MUSE programme in Period 102 (Principal Investigator: Tramper) is targeting two fields in Sextans A ($Z \sim 0.1\ Z_{\odot}$) for this very reason — one centred on a region rich with nebular structures and apparent active star-formation, a second in the centre of the galaxy which (naïvely) appears more quiescent.

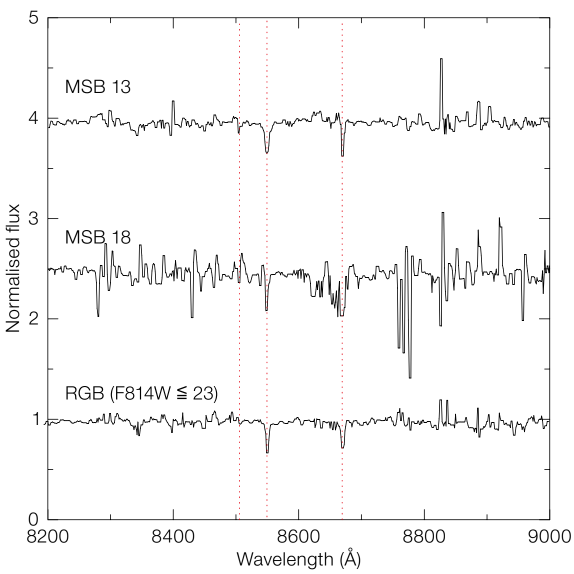

Figure 5. The Ca II triplet region for the two brightest AGB stars (offset by 1.5 continuum units, with identifications from McQuinn et al., 2013) and the co-added spectra of the 16 brightest stars at the top of the red giant branch. The wavelengths of the Ca II triplet, shifted to the radial velocity of Leo P, are indicated by the vertical red lines.

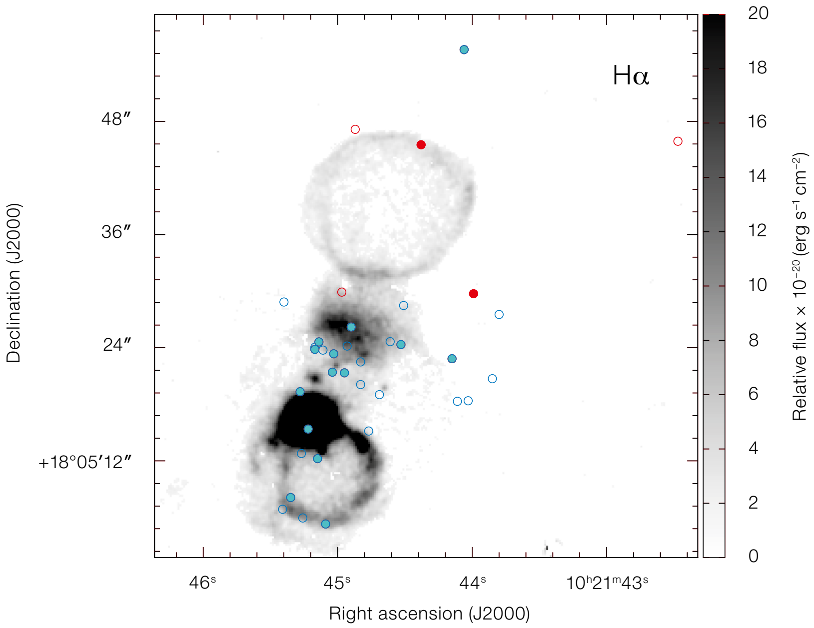

Figure 6. Intensity map of Hα emission in Leo P from the MUSE observations. The overlaid symbols match those in Figure 2 and show the locations of the stars with initial spectral classifications. Note the substantial (~100 pc-scale) ring structures traced by the gas emission.

The MUSE observations of Leo P have given us our first comprehensive view of resolved massive stars in a dwarf galaxy with substantially sub-solar metallicity (3%); also see Evans et al. (2019). Detailed models for the evolution of such stars are available from, for example, Szécsi et al. (2015), but we are unable to test their predictions without empirical results for stars in this regime. We have confirmed that the central source in the H II region has an O-type spectrum, and we argue this is probably the lowest metallicity massive star found to date; whether it is a bona fide single star or a multiple/composite system (with a correspondingly big impact on the overall feedback in terms of ionising photons) will require future follow-up. The MUSE spectroscopy has also given us a first glimpse of what appear to be very metal-deficient AGB stars, which will be important reference targets to investigate dust production channels at low metallicity and to provide empirical calibration of evolutionary models.

Even with the impressive performance of MUSE, quantitative analysis of the bulk of the hot- and cool-star populations of Leo P will require the greater sensitivity of new facilities. In particular, the first-light High Angular Resolution Monolithic Optical and Near-infrared Integral-field spectrograph (HARMONI) spectrograph on ESO's Extremely Large Telescope (ELT) will provide the excellent angular resolution and sensitivity needed to probe the properties (abundances, dynamics) of the evolved-star population in Leo P (for example, Gonzalez & Battaglia, 2018). Ultimately, we also want ultraviolet spectroscopy of massive stars in systems like Leo P to investigate their wind properties — this is unrealistic with the HST, but would be well within the grasp of the Large UV Optical InfraRed Surveyor (LUVOIR) and Habitable Exoplanet Observatory (HabEx) concepts currently under study by NASA as part of the ongoing Decadal Survey.

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The Belt of Venus effect, an atmospheric phenomenon caused by backscattered sunlight, seen at twilight at the VLT.

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Witnessing the Early Growth and Life Cycle of Galaxies with KMOS^{3D}

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Near-infrared integral field unit (IFU) spectrographs are powerful tools for investigating galaxy evolution. We report on our recently completed multi-year KMOS^{3D} survey of Hα, [N II] and [SII] line emission of galaxies at redshift z ~ 0.7–2.7 with the *K*-band Multi-Object Spectrograph (KMOS) at the Very Large Telescope (VLT). With deep observations of 745 targets spanning over two orders of magnitude in galaxy mass, five billion years of cosmic time, and all levels of star formation, KMOS^{3D} provides an unparalleled population-wide census of spatially-resolved kinematics, star formation, outflows and nebular gas conditions. The dataset sheds new light on the physical mechanisms driving the early growth and lifecycle of galaxies, and provides a rich legacy for the astronomical community.

The regulated growth of galaxies at "cosmic noon"

Extensive panchromatic look-back surveys have now mapped the global evolution of star formation and nuclear activity, stellar mass buildup, and gas content of galaxies out to redshift z ~ 3, spanning 85% of the Universe's history. At z ~ 2, 10 billion years ago, the cosmic star formation and supermassive black hole accretion rates peaked at ~ 20 times present-day levels, and cold molecular gas accounted for as much as half the baryonic mass of galaxies. At this epoch, often dubbed "cosmic noon", ~95% of star-forming galaxies (SFGs) already lie on a tight main sequence (MS), their star formation rate (SFR) being roughly proportional to their stellar mass, SFR $\propto M_*$. These early SFGs also show relationships between their stellar mass, size, gas content, and metallicity. The growth of galaxies at cosmic noon thus appears to be tightly regulated until they reach M_* ~ 10^{11} M_*, when their star formation activity is rapidly quenched.

These observations have established the broad scope of the equilibrium growth model, in which accretion from the cosmic web and minor mergers fairly continuously replenish the gas reservoirs of SFGs, and the balance between accretion, star formation, and outflows governs their evolution. Given the different conditions prevailing in early SFGs, detailed *in-situ* observations are necessary to understand which processes regulate their evolution, how the disc and spheroidal components of present-day galaxies arise, and why star formation shuts down at high masses.

The role of near-infrared integral field unit surveys and KMOS^{3D}

Spatially and spectrally resolved information on the kinematics, star formation, and condition of the interstellar medium on sub-galactic scales provides insights into the physics that drives the early evolution of galaxies. Nebular emission lines such as Hα, [N II], [S II] and [O III] are powerful tools for investigating these properties. At z ~ 1–3, these optical lines at rest are redshifted into the near-infrared (near-IR, λ ~ 1–2.5 μm) and strongly dimmed. Dissecting distant galaxies requires sensitive near-IR instrumentation and a large collecting area. Observations with the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) at the VLT and other near-IR single-object IFUs on 8–10-metre telescopes (for example, Förster Schreiber et al., 2011; Glazebrook, 2013) yielded the first compelling evidence that the majority of massive z ~ 2 SFGs are rotating yet turbulent discs, rather than disturbed major mergers. These pioneering studies uncovered the role of galaxy-internal processes, such as violent disc instabilities, in the gas-rich SFGs at z ~ 1–2, laying some of the foundations of the equilibrium growth framework. With 24 deployable IFUs, KMOS at the VLT brought the next breakthroughs by enabling near-IR IFU surveys of much larger and more complete samples.

We have carried out KMOS^{3D}, a comprehensive 75-night Guaranteed Time Observation (GTO) survey of Hα+[N II]+[S II] emission of 745 mass-selected galaxies at $z \sim 0.7$–2.7 (Wisnioski et al., 2015). The cornerstones of the survey strategy were: 1) wide and homogeneous coverage of galaxy stellar mass, SFR, colours, and redshift; 2) the same spectral diagnostics across the entire redshift range; and 3) deep integrations to map faint, extended line emission. The targets were drawn from the Hubble Space Telescope (HST) 3D-HST Treasury Survey (for example, Momcheva et al., 2016), which provided a well characterised parent sample with source detection and accurate redshifts relying on rest-optical properties, largely reducing the bias towards blue, actively star-forming galaxies resulting from rest-ultraviolet identifications. 3D-HST overlaps with the CANDELS fields, with high-resolution HST optical and near-IR imaging, and with extensive X-ray to far-IR/radio coverage.

The KMOS^{3D} selection criteria were:
(1) $M_* > 10^9\ M_\odot$ and a magnitude cut of $K_{AB} < 23$ mag;
(2) a redshift $0.7 < z < 2.7$;
(3) the emission lines of interest falling in atmospheric windows away from bright sky lines.

By avoiding selection on colours or properties sensitive to star formation or AGN activity, and by covering five billion years of cosmic time, KMOS^{3D} is optimally suited for population censuses and evolutionary studies.

Figure 1 shows the distribution of the KMOS^{3D} sample in stellar mass versus SFR. The *K*-band magnitude cut ensures 95% completeness for $\log(M_*/M_\odot) > 9.7$ at $0.7 < z < 1.1$; $\log(M_*/M_\odot) > 10.2$ at $1.3 < z < 1.7$; and $\log(M_*/M_\odot) > 10.5$ at $1.9 < z < 2.7$ — these correspond to the redshift slices where Hα is observed in the *YJ*-, *H*-, and *K*-bands, respectively. The corresponding median on-source integration times are 5, 8, and 9 hours respectively, and range up to 20–30 hours. The median resolution is 0.5 arcseconds, or ~ 4 kpc at at $z \sim 0.7$–2.7. Down to SFRs ~ 1/7 of the MS (comprising 80% of the sample), 90% of the objects are detected in Hα and 80% of them are resolved. Unsurprisingly, the detection rate drops among more quiescent galaxies, but even ~ 25% of those are detected, and a third of them are resolved. Selected key results are highlighted here.

The prevalence of rotationally supported turbulent gas-rich discs

First and foremost, the spatially-resolved gas motions derived from the Hα emission line profile across the KMOS^{3D} galaxies robustly confirmed that the majority (> 70%) of high-redshift SFGs are rotating discs (Figure 2). The data also confirmed the elevated gas turbulence of high-redshift discs, with typical intrinsic disc velocity dispersions $\sigma_0 \sim 50$ km s^{-1} at $z \sim 2.3$ and ~ 30 km s^{-1} at $z \sim 0.9$ (Figure 3). The increase of the velocity dispersions with redshift is in line with expectations for gravity-driven turbulence in marginally stable gas discs and the cosmic evolution in gas fractions, where heating is caused by rapid gas flows onto and within the galaxies (for example, Genzel et al., 2011; Krumholz et al., 2018).

Bulge formation, outer disc kinematics, and the dominance of baryons

Dissipative processes should be particularly efficient in discs at $z \sim 1$–3 given their gas-richness and elevated turbulence. The associated inward mass transport and angular momentum loss could lead to bulge formation on Gyr timescales. Massive stellar bulges are in place, and large nuclear concentrations of molecular gas have been uncovered as early as $z \sim 2.5$ in massive star-forming discs (for example, Lang et al., 2014; Tadaki et al., 2017). Measurements of the angular momenta of KMOS^{3D} discs further support bulge formation via disc-internal mechanisms (Burkert et al., 2016). The specific angular momenta of the discs anti-correlate with their galaxy-wide stellar and gas mass surface densities, but exhibit no significant trend with stellar mass surface densities in the inner 1 kpc. Accumulation of low angular momentum material to form bulges in the disc centres thus appears to be decoupled from the mechanisms that set disc structure and angular momentum on global galactic scales.

KMOS^{3D} has strengthened the key finding from smaller samples that $z \sim 1$–2.5 SFGs are not only gas-rich but also strongly

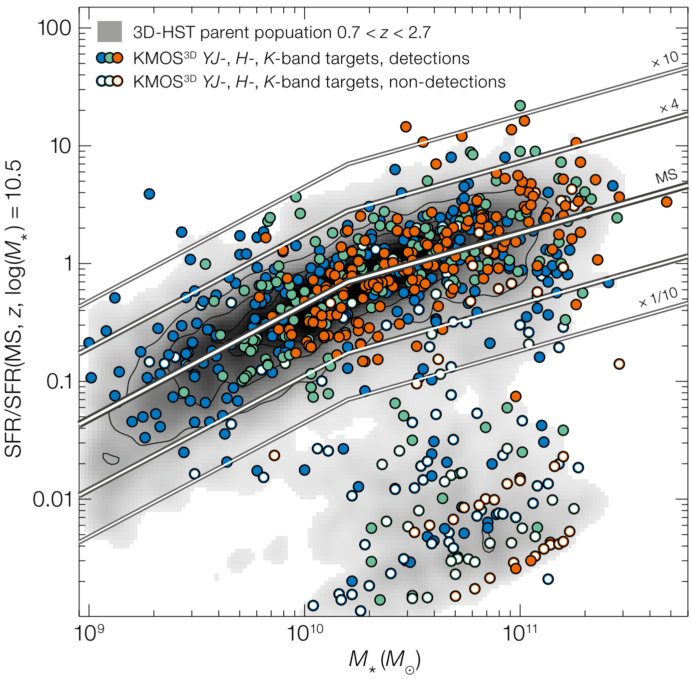

Figure 1. Distribution of the 745 KMOS^{3D} targets in stellar mass versus SFR normalised to that of the MS at the redshift of each galaxy and $\log(M_*/M_\odot) = 10.5$. The shape of the MS (from Whitaker et al., 2014) and offsets by factors of 4 and 10 above and below the relationship are plotted as solid lines. Coloured symbols represent targets observed in the *YJ*-, *H*-, and *K*-bands (as labelled). KMOS^{3D} probes the underlying population of massive galaxies at $0.7 < z < 2.7$ and $K_{AB} < 23$ mag well, the density distribution shown in grey shades.

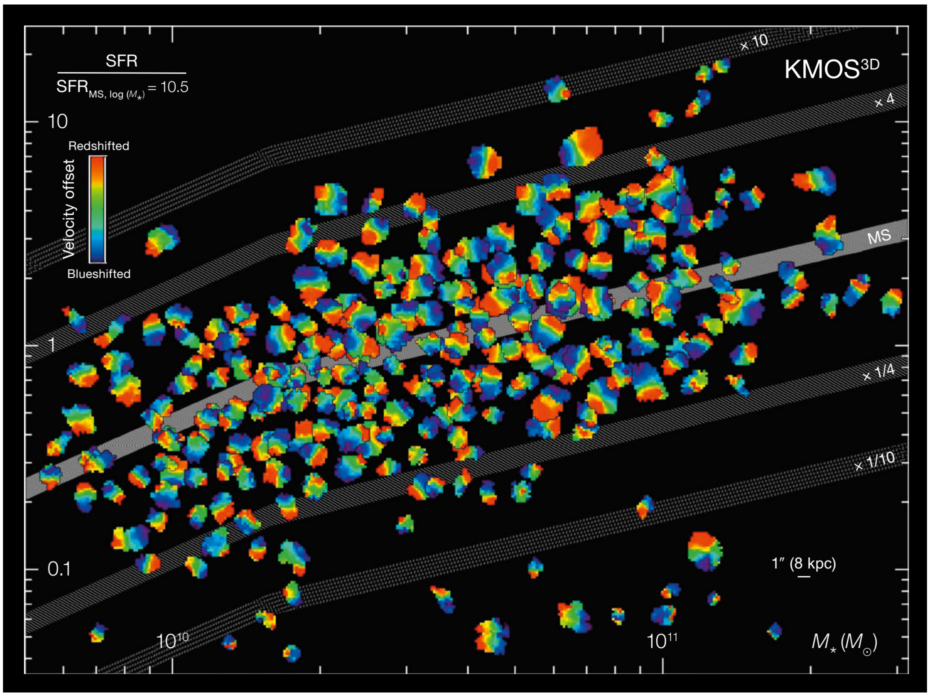

Figure 2. Overview of the Hα velocity fields for 250 resolved and representative KMOS^{3D} galaxies (half at z ~ 0.9 and half at z ~ 2.3), plotted on the same angular scale and in the same parameter space as in Figure 1. The monotonic velocity gradients, as well as other characteristic properties of ordered rotation in discs, are identified in the majority of the galaxies, and even among several galaxies well below the MS.

baryon-dominated on scales of ~ 10–15 kpc (Figure 3). Kinematic modelling of 240 well-resolved discs with high S/N data showed that gas and stars dominate the total dynamical mass budget, making up ~ 55% of it on average and reaching ~ 90% at z ~ 2.3, leaving little room for dark matter within the disc's half-light radius $R_{1/2}$ at $z > 2$ (Wuyts et al., 2016b). However, the scatter in baryonic mass fractions at fixed redshift is large as a result of correlations with mass surface densities. These effects are reflected in the evolution of the Tully-Fisher relation, connecting the disc circular velocity and mass, from KMOS^{3D} (Übler et al., 2017). A combination of three factors can explain the trends in both the mass budget and the Tully-Fisher relation: the gas and baryonic fractions of the discs increase with lookback time as enhanced cosmic accretion promotes high baryon concentrations at the centre of dark matter halos; these halos have shallow profiles; and more compact discs do not probe as far into their host dark matter halo.

Recent exploration of the outer rotation curves of high-redshift discs led to the exciting discovery of steep declines in velocity beyond a peak at radius $r \sim 1.3\,R_{1/2}$, in stark contrast to the findings at low redshift. In very deep SINFONI observations of six high-mass SFGs probing out to 2–3 times the half-light radius, the slopes are as steep as or steeper than the Keplerian decline ($v_{rot}\,r^{-1/2}$) for a disc purely supported by rotation, and detailed modelling implies dark matter fractions of 20% within

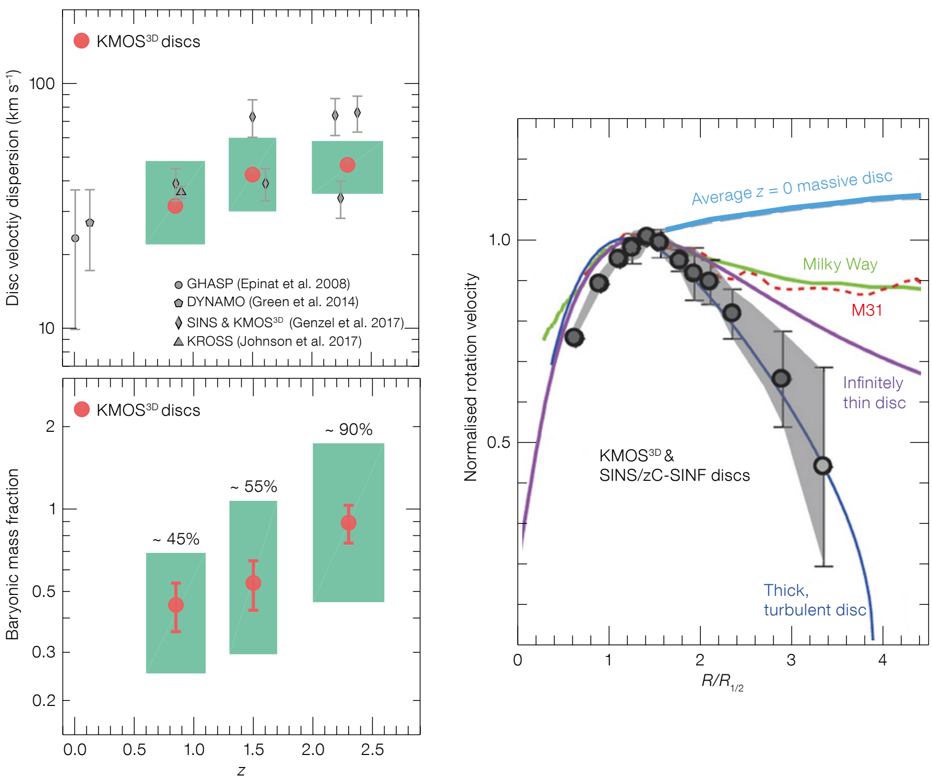

Figure 3. Disc velocity dispersions, baryonic mass fractions on disc scales, and composite rotation curve of z ~ 0.7–2.7 discs. In the left panels, median values and 68% percentiles of the distributions for KMOS^{3D} discs in three redshift slices are plotted as red circles and green boxes. In the top left panel, selected results from IFU observations of Hα from other samples, and from individual galaxies with the most detailed constraints, are included (see legend). In the right panel, the effects of the elevated gas turbulence and baryon fraction at high redshift are reflected in the composite rotation curve based on stacked data and individual velocity curves from KMOS^{3D} and the SINS/zC-SINF SINFONI survey (filled circles and grey polygons, respectively). The decline at large radii is steeper than for pure rotation in a disc of similar mass, and is in stark contrast to the much flatter slopes in massive z ~ 0 discs, including the Milky Way and M31, that are dominated by dark matter in their outer disc regions (coloured lines).

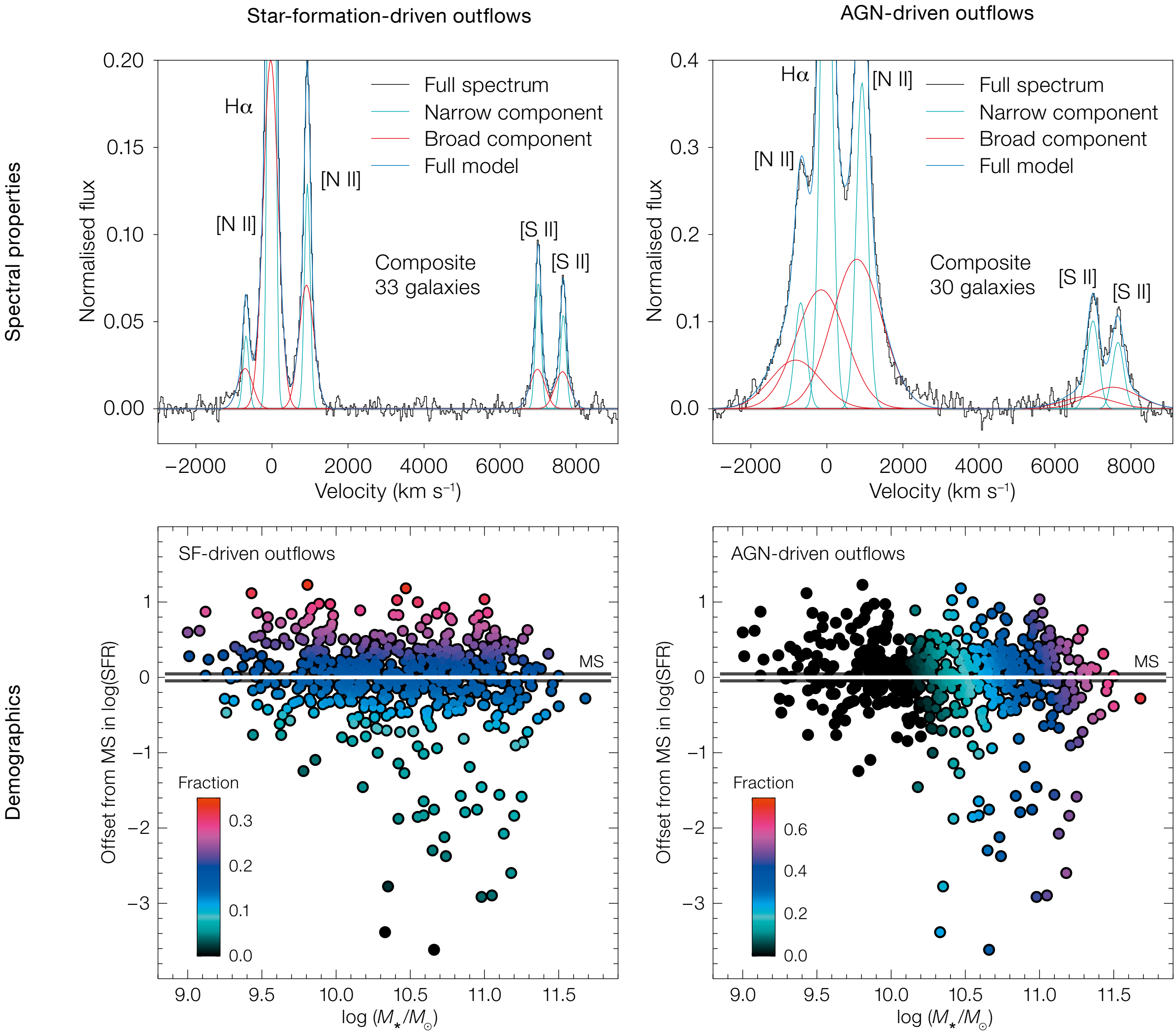

Figure 4. Distinct spectral properties and demographics of star-formation-driven (left) and AGN-driven (right) galactic-scale winds obtained from ~ 600 galaxies at $0.7 < z < 2.7$ mostly from KMOS^{3D}. The composite spectra (top panels) from the best quality data are plotted with black lines, and the best-fit narrow+broad component emission tracing H II regions and outflows are shown in cyan and orange, respectively. The trends in outflow incidence with stellar mass and offset from the MS at the mass and redshift of each galaxy (bottom panels) are coded according to the colour bars in each panel and sampled at the locations of the individual objects.

a half-light radius (Genzel et al., 2017). KMOS^{3D} substantiated this breakthrough by showing, through a novel stacking technique, that outer rotation curves declining to 3–4 times $R_{1/2}$ are likely to be a widespread feature of $\log(M_*/M_\odot) \sim 9.5$ star-forming discs around cosmic noon (Lang et al., 2017). In local spiral galaxies, the typically flat rotation curves are the hallmark of dominant dark matter in outer disc regions. At high redshift however, the dominance of baryons within the shallower inner dark matter potential leads to declining rotation curves, with the considerable dynamical support from random motions further steepening the falloff. These results support the lesser role of dark matter on disc scales implied by the mass budget and Tully-Fisher studies, independently of assumptions about the light-to-baryonic-mass conversions. These findings also link massive $z \sim 1$–3 SFGs to their descendants — high-mass early-type galaxies and strongly bulged discs at $z \sim 0$ — which also have low central dark matter fractions.

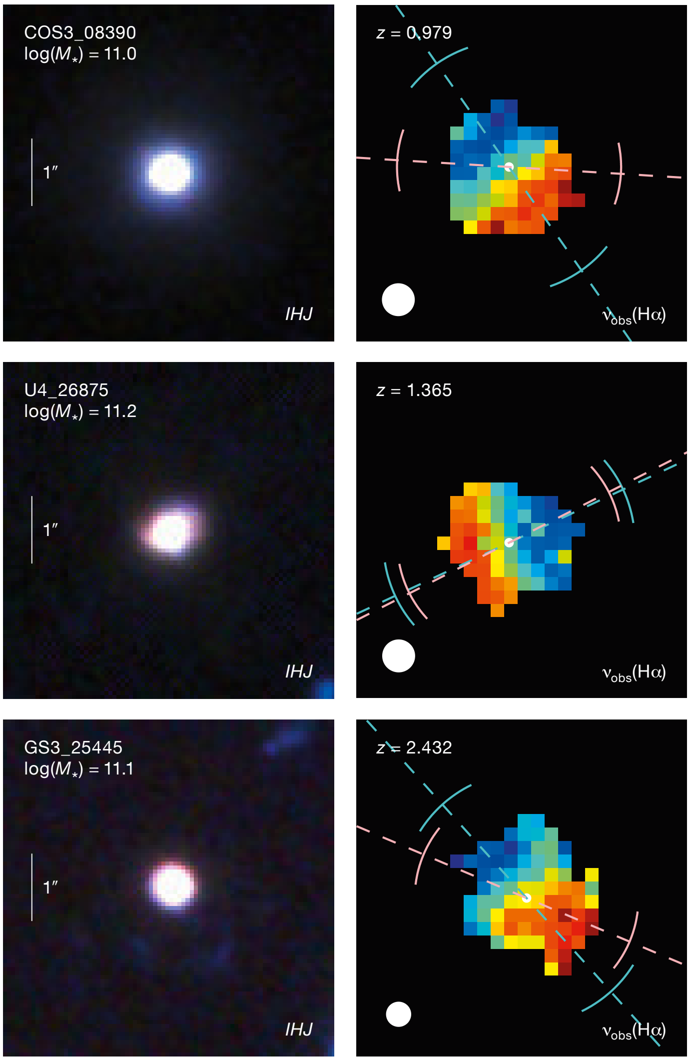

Figure 5. Three examples from among 35 massive compact SFGs observed in KMOS^{3D}. Their HST *IJH*-band morphologies reveal a dominant dense compact stellar component (left panels). KMOS observations of their Hα velocity fields are shown in the right panel; the white circle diameter corresponds to the FWHM of the point spread function of the data. Most of these KMOS observations revealed clear signatures of ordered rotation, supporting the scenario in which they are the immediate progenitors of compact disc-like quiescent galaxies at high redshift.

Demographics and physical properties of galactic outflows

Galactic winds have long been observed in distant SFGs and luminous quasars via high-velocity, blue-shifted absorbing gas detected in galaxy-integrated rest-ultraviolet spectra. In rest-optical nebular line emission, outflows manifest themselves as a broad component lying underneath a narrower component from star formation; their separation is facilitated with IFU data. SINFONI observations of a few tens of objects with ~ 1–2 kpc resolution detected star formation (SF)-driven outflows, characterised by broad emission with FWHM ~ 400–500 km s^{-1}, across the discs. They are typically associated with brighter star-forming clumps, while faster winds (FWHM ~ 1000–2000 km s^{-1}) originate from the nuclear regions in the most massive galaxies hosting an AGN. Analysis of Hα+[N II]+[S II] emission of ~ 600 galaxies spanning 9 < log($M_*/M_\odot$) < 11.7, mostly from KMOS^{3D}, revealed the distinct demographics and physical properties of outflows (Figure 4, Förster Schreiber et al., 2018; also Genzel et al., 2014). The prevalence of SF-driven outflows depends on star formation properties, with fractions increasing above the MS and reaching up to ~ 40% at SFR surface densities > 1 $M_\odot$ yr^{-1} kpc^{-2}. In contrast, AGN-driven outflows are rare below log($M_*/M_\odot$) ~ 10.7 and rapidly become ubiquitous above this mass, being present in ~ 75% of log($M_*/M_\odot$) > 11.2 galaxies. Similar to AGN, their incidence depends primarily on stellar mass and its central concentration, but is higher than that of AGN identified by any one diagnostic alone (for example, X-ray properties), thus reflecting the variability of the AGN phenomenon in different tracers. The homogeneous sampling and deep integrations of KMOS^{3D} observations indicate that the incidence trends are not caused by S/N variations across galaxy parameter space. The outflows, along with the elevated disc turbulence, are expected to efficiently redistribute metals within the galaxies, and could explain the typically flat radial metallicity gradients inferred from KMOS^{3D} maps of the diagnostic [N II]/Hα flux ratio (Wuyts et al., 2016a).

The velocities of SF-driven winds vary little with galaxy mass, implying that the relative bulk of expelled gas escapes only from log($M_*/M_\odot$) ≲ 10.3 systems, while more massive galaxies drive so-called "fountains". Surprisingly, the inferred mass outflow rates $\dot{M}_{out}$ are only ~ 0.1–0.2 times the SFRs at all galaxy masses, at odds with theoretical work that requires mass loading factors $\eta = \dot{M}_{out}$/SFR above unity and $\propto 1/M_*^{0.35-0.80}$ to reproduce the observed slope of the galaxy mass–metallicity and galaxy mass to halo mass relationships at log($M_*/M_\odot$) < 10.7. This tension could be alleviated if substantial amounts of mass, momentum, and energy are contained in much hotter and/or colder wind phases than the ~ 10^4 K ionised gas probed by Hα, as inferred in nearby starburst winds.

The faster, high-duty-cycle AGN-driven winds at high masses have mass loading factors comparable to those of the SF-driven winds but carry 10 times as much momentum and 50 times as much energy, so they can escape the galaxies, contribute to heating halo gas, and help prevent further gas infall. Numerical simulations suggest that such a mechanism, which also acts at the modest AGN luminosities and Eddington ratios of the majority of the KMOS^{3D} AGN, may be more effective at widespread and long-term galaxy quenching than ejective QSO-mode feedback in rare, high luminosity, high-Eddington-ratio AGN. The sharp increase in the incidence of AGN-driven outflows near the transition mass above which passive galaxies become prevalent and both galactic molecular gas fractions and specific SFRs drop steeply, strengthens the notion of a causal link between AGN activity and quenching.

Star-forming discs and rejuvenation in compact galaxies

A strength of the KMOS^{3D} strategy is to allow a systematic exploration of emission line properties in rarer subsets of galaxies, with consistent comparisons to the underlying population. Massive compact SFGs at $z \sim 1–3$ have received much attention in recent years as potential immediate progenitors of dense massive quiescent galaxies. In two-thirds of the 35 compact SFGs observed in KMOS^{3D}, spatially resolved line emission reveals rotating gas discs with up to twice the extent of the compact stellar cores (Figure 5; Wisnioski et al., 2018). Their kinematic properties are similar to those of mass-matched, more extended SFGs in KMOS^{3D}. They host AGN 1.4 times more often, in agreement with other recent studies, and they commonly drive powerful nuclear outflows. The rotation observed in the compact SFGs, and the growing evidence from morphologies and stellar kinematics that high-redshift passive galaxies are disc-like systems, support this evolutionary link.

Pushing into a regime so far unexplored with IFUs at $z > 1$, line emission was also detected in ~ 20% of the KMOS^{3D} targets classified as quiescent based on their rest-frame colours (Belli et al., 2017). Half of them exhibit spectral signatures revealing the persistence of AGN activity and gas outflows well into quenching. In the other sources, the Hα luminosities confirm the low star formation activity with SFR(Hα) ~ 0.2–7 $M_{\odot}$ yr^{-1}, but, surprisingly, their average [N II]/Hα ratio indicates metallicities ~ 3 times lower than in MS SFGs of the same mass, and half also exhibit resolved gas discs. These properties suggest rejuvenation, where the low-level star formation is fuelled by recent accretion of metal-poor gas via cosmic flows or minor mergers rather than being associated with advanced stages of disc fading.

Outlook

The rich scientific outcome of surveys such as KMOS^{3D} and other major campaigns at the VLT underscores the tremendous value of large and coherent observing programmes in advancing our knowledge of galaxy evolution. Comparable efforts in the future with KMOS, other instruments at the VLT, and other facilities such as ALMA and NOEMA will be important to better trace the baryon cycle in and out of galaxies, constrain their stellar composition and kinematics, and systematically explore their cold interstellar medium at all accessible redshifts — paving the way towards the Extremely Large Telescope and James Webb Space Telescope era.

Acknowledgements

We thank the ESO staff on Paranal for excellent and enthusiastic support throughout the five years and numerous runs during which the KMOS^{3D} observations were collected.

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VLT colour-composite image of the centre of the starburst galaxy NGC 1313; the filters used are *R*, *B*, *z* and narrow-band Hα, [O I] and [O III].

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Shedding Light on the Geometry of Kilonovae

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We present the first results of a campaign aimed at characterising the linear polarisation signals and thus the geometry of binary neutron star mergers (i.e., kilonovae). We carried out the first polarimetric observations of a kilonova called AT 2017gfo, using the FOcal Reducer/low dispersion Spectrograph 2 (FORS2). We predicted for the first time the polarisation signatures expected from kilonovae and highlighted the best strategy to detect linear polarisation in future events. Our studies demonstrate how the detection of polarisation will constrain crucial parameters of these systems, such as the inclination and composition, distribution and extent of the different components of the ejecta.

The first discovery (Abbott et al., 2017) of both a gravitational wave source GW170817 and its electromagnetic counterpart AT 2017gfo[a] marked year zero of the multi-messenger gravitational-wave era, and has been the subject of about 500 articles posted on the preprint server arXiv[1] in the past year. The gravitational wave was generated by the merger of two neutron stars and gave rise to an electromagnetic transient — called a kilonova — which was intensively monitored with all the main ground-based and space-borne facilities. This single event provided the smoking gun for a number of unresolved discussions, for example, on the nature of short gamma-ray bursts and the origin of *r*-process elements in the Universe.

Despite the general agreement between existing models and data, some crucial ingredients are still missing. State-of-the-art simulations and the analysis of AT 2017gfo suggest that the material ejected in kilonovae is likely to be distributed in two distinct components (see cartoon in Figure 1): a component around the merger plane that is relatively faint and red — characterised by the presence of heavy elements (including lanthanides with high opacities) — and a relatively bright and blue component at higher latitudes, characterised by relatively light elements. However, critical parameters of the system like inclination, mass, velocity, and composition and distribution of the ejecta components are still uncertain despite their being crucial, for example, in the estimation of kilonova rates, the comparison of yields to cosmic abundances, and the derivation of the Hubble constant. This is where polarimetry can come to the rescue.

Polarisation is sometimes an unsettling quantity to think about as, unlike the other two and more familiar properties of light — brightness and colour — it is almost impossible to observe with the naked eye. It is, however, an extremely powerful tool for studying the geometry of extragalactic sources such as kilonovae, which are otherwise too far away to be spatially resolved using other imaging techniques. Radiation from kilonovae can be linearly polarised by electron scattering, or depolarised by interactions with atoms. Linear polarimetry is thus sensitive to the geometry of the ejecta, the distribution of elements within

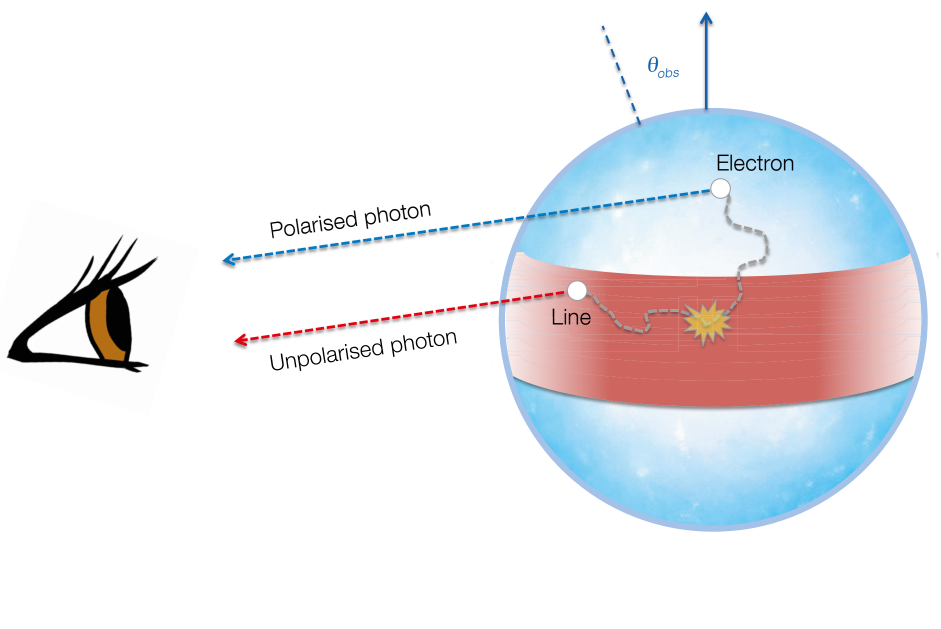

Figure 1. A cartoon illustrating the origin of polarisation in kilonovae. Photons escaping the ejected material from the red component are preferentially depolarised by line interactions, while those leaving the ejecta from the blue component are more likely to be polarised by electron scattering. These both contribute to the total polarisation signal that could be observed in future kilonova events.

the ejecta, and the interplay between different sources of opacity. This allows us to study properties that are not easily constrained through the analysis of photometric light curves and spectra alone.

Polarisation of AT 2017gfo

We presented polarimetric data of AT 2017gfo taken with FORS2 in Covino et al. (2017). Five epochs were secured, spanning a range between about 1.5 and 10 days after the binary neutron star merger. A polarisation signal of $P = 0.50 \pm 0.07\%$ and a polarisation angle, PA = $57° \pm 4°$ were measured during the first observation. Stringent upper limits were placed on the following epochs, all consistent with the former measurement.

Despite the detection of a polarisation signal in the first epoch, determining what fraction of this is intrinsic to the kilonova and what fraction is due to polarisation induced by dust along the line of sight is not trivial. In fact, the polarisation percentage and angle observed for AT 2017gfo are both consistent with those shown by several stars in the field of view. This suggests that a good fraction of the signal detected is due to dust in our galaxy, and that the intrinsic emission was therefore weakly polarised.

The origin of polarisation in kilonovae

In a follow-up paper, we predict the polarisation signal expected from a kilonova for the first time, and identify the best strategy to constrain important parameters of the system in future polarimetric observations (Bulla et al., 2018). We focus on the optical emission, as this is where kilonovae are brightest and thus most easily detectable using ESO facilities.

As illustrated in Figure 1, our work demonstrates that the presence of two separate ejecta components gives rise to a detectable polarisation signal in kilonovae. While photons coming from the red component are typically depolarised by interactions with atoms, photons from the blue component are preferentially scattered off, and polarised by, electrons. This leads to a net polarisation signal that can reach ~ 1% levels for favourable inclinations of the system (i.e., for an equatorial viewing angle; see Figure 2).

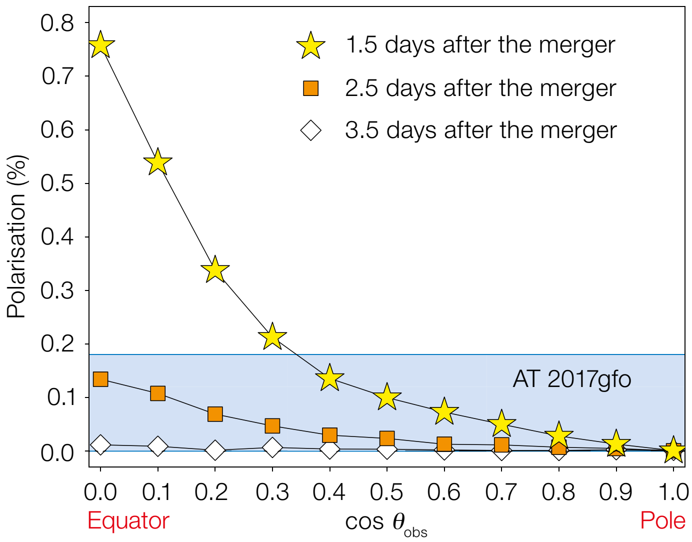

Figure 2. Polarisation predicted by our simulations as a function of the observer orientation, from the equator ($\cos\theta_{obs} = 0$) to the pole ($\cos\theta_{obs} = 1$). Different symbols correspond to different epochs after the merger of two neutron stars. The blue shaded area marks the range of polarisation estimated for AT 2017gfo.

Our simulations predict that the polarisation signal should reach a maximum at around 7000 Å and become negligible about two or three days after the merger for all observer orientations. These predictions are crucial for planning future polarimetric campaigns, highlighting that early (within two days of the event) observations around 7000 Å are required to detect polarisation in kilonovae.

Our modelling also suggests that any signal observed after three days would not be intrinsic (see white diamonds in Figure 2) but rather due to intervening interstellar dust. Since dust polarisation is constant with time, this provides a simple way to characterise the interstellar signal from late-time polarimetry and remove it from the polarisation intrinsic to the kilonova detected earlier. In the case of AT 2017gfo, we estimated the interstellar polarisation to be $0.49 \pm 0.05\%$, leading to an upper limit on the intrinsic polarisation of $P < 0.18\%$ (see shaded area in Figure 2). The better handle on the intrinsic signal of AT 2017gfo allows us to constrain the inclination of the system to within 60° of the polar direction ($\cos\theta_{obs} \geq 0.4$, see Figure 2), a value which is consistent with independent measurements from the literature.

Although the polarisation signal is consistent with zero (i.e., unpolarised) in this particular event, the detection of non-zero polarisation in future kilonovae will unambiguously reveal the presence of a lanthanide-free blue component of the ejecta. Because of the competition between polarising radiation from the blue component and depolarising radiation from the red component, the polarisation signal is predicted to be strongly dependent on the relative extent of the ejecta components for inclinations close to the merger plane. The detection of a polarisation signal in future events at favourable orientations will therefore place constraints on the spatial and angular distribution of the two ejecta components.

A bright future ahead

In these studies, we have: (i) established the origin of polarisation in kilonovae; (ii) made quantitative predictions about the polarisation signal as a function of observer orientation and time; (iii) highlighted the best strategy to drive a future polarimetric observing campaign; (iv) identified a simple approach to estimate the interstellar polarisation from late-time observations and thus to disentangle the intrinsic and interstellar signals from earlier epochs; (v) constrained the system inclination of AT 2017gfo; and (vi) demonstrated how the detection of polarisation in future kilonova events can unveil the spatial extent of the two ejecta components.

The best is yet to come! LIGO, the Laser Interferometer Gravitational-Wave

Observatory and the Virgo interferometer will begin taking data again in a couple of months, discovering many more kilonovae that we could follow up with polarimetry. The flexibility and reliability of ESO facilities is a strong factor in this exciting and innovative quest.

The detection of polarisation in future kilonova events, coupled to the predictions made by our modelling, will unambiguously reveal the presence of a lanthanide-free blue component and allow us to constrain important parameters like the geometry of the ejecta components and the inclination of the system.

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Links

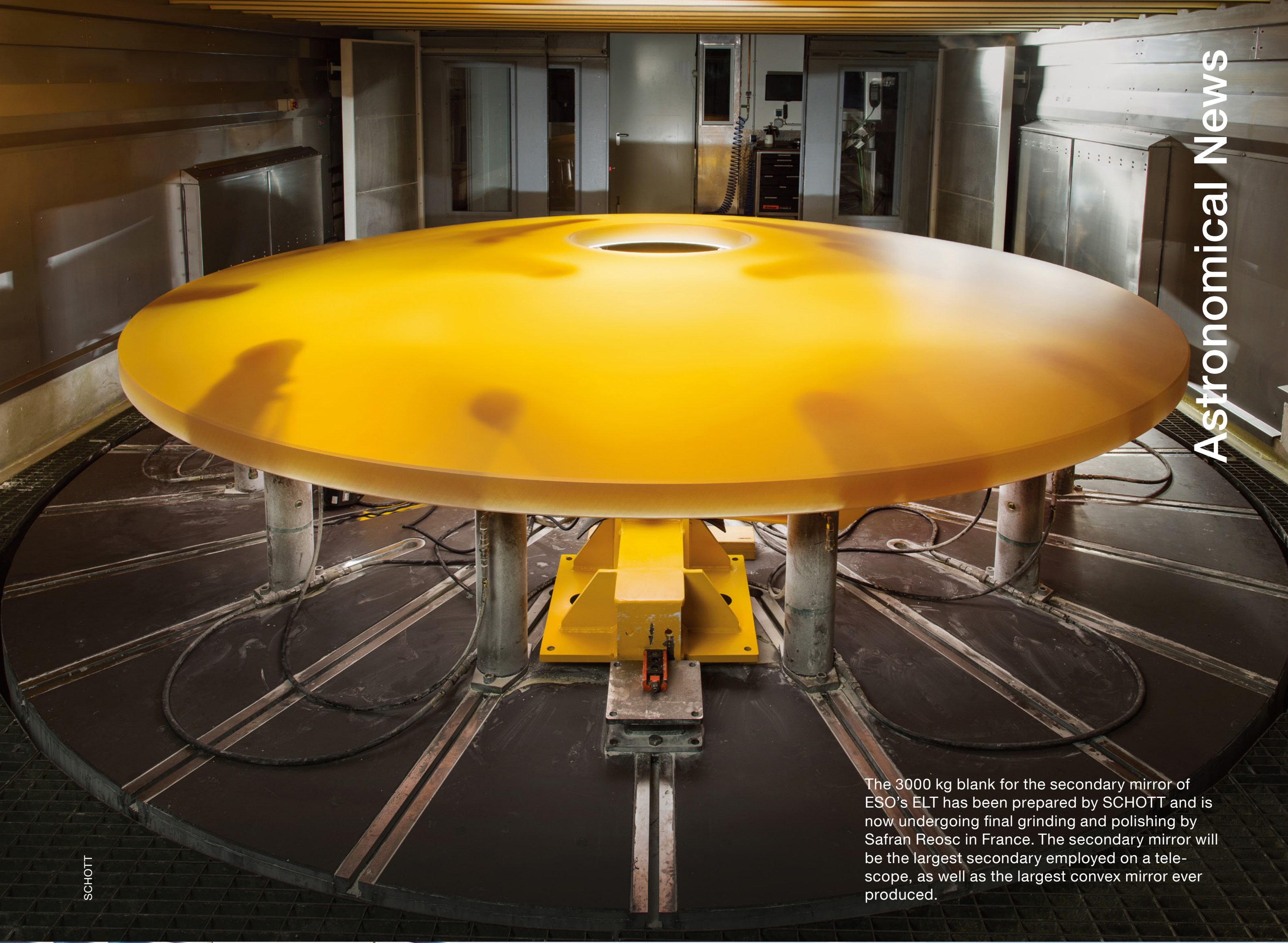
[1] The astrophysics arXiv preprint server: https://arxiv.org/archive/astro-ph

Notes

[a] The name of the kilonova AT 2017gfo was assigned by the Transient Name Server, the official IAU server through which new astronomical transients are reported.

V. Forchi/ESO

Unit Telescope 1 (called Antu) hosts FORS2, probably the most versatile instrument at the VLT.



SCHOTT

The 3000 kg blank for the secondary mirror of ESO's ELT has been prepared by SCHOTT and is now undergoing final grinding and polishing by Safran Reosc in France. The secondary mirror will be the largest secondary employed on a telescope, as well as the largest convex mirror ever produced.

HARMONI Consortium

Members of the HARMONI consortium in Lyon. The High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI) will be one of the first instruments on ESO's ELT.

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ESO Conference Proceedings 2.0 at Zenodo

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As of the past few years, ESO no longer publishes conference proceedings, mainly because of the large effort involved in their production and the relatively small impact of proceedings papers. In order to continue to preserve a record of ESO-hosted conferences, the ESO Library has implemented a system called "Conference Proceedings 2.0". Presentation slides and posters are made available through Zenodo, a CERN-developed platform for the permanent storage of digital research output, ensuring that content is citable, discoverable, and archived.

For many decades, conference proceedings formed a vital part of the astronomy literature. Astronomers typically present their latest findings at scientific meetings, and the resulting conference papers provided valuable information about ongoing research to those colleagues who could not attend the conference, and preserved the results for posterity. For the researchers, writing up their presentations often formed the basis for a more detailed, refereed article.

ESO has a long history of publishing proceedings volumes of the workshops and conferences it hosted. From 1969 to 2002 ESO issued the ESO Conference and Workshop Proceedings which were produced and published in-house. In a joint project involving the ESO Library and the NASA Astrophysics Data System Abstract Service (ADS), many of these volumes have been scanned and made available in electronic format to the entire astronomy community. The PDF files can be accessed via the Library catalogue[1] or directly at the ADS[2]. In the following years, the ESO Astrophysics Symposia series was published by Springer[3].

However, 10 years ago the impact of conference proceedings in the natural sciences was already known to be declining, with proceedings papers becoming obsolete faster than scientific literature in general (Lisée, Larivière & Archambault, 2008). In light of the reduced impact of conference proceedings, and because of the large effort (on the part of authors and editors) as well as the costs involved in the production of conference proceedings, it was decided to discontinue the symposia series. The last volume was published in 2009. In the mid-2000s, some organisers started posting presentation slides of conferences on the web; however, this approach was inconsistent, and the content prone to deletion after the meetings.

Next-generation conference proceedings

Despite the cessation of ESO's conference proceedings series, the Library still considered it important to preserve the legacy of content presented at ESO-hosted meetings. Obviously, the problems encountered with the series volumes needed to be avoided, and establishing records of conference material had to be as straightforward and cost-effective as possible. An idea was developed to take presentation slides and poster PDFs (which are prepared for the conference anyway), add descriptions (metadata) to the individual records, and archive them in a central place. In this way, the Library sought to establish "ESO Conference Proceedings 2.0", adapted to the digital age.

In their search for a suitable platform, the librarians encountered Zenodo[4]. Developed by the European Organization for Nuclear Research (known as CERN) in the context of the European Commission's OpenAIRE project[5], Zenodo is a repository for all kinds of research artefacts that form part of the scholarly process, and which are not published elsewhere. Such individual research output is often referred to as "the long tail of science". Zenodo's lead software developer describes the content as follows: "Data, software and other artefacts in support of publications may be the core, but equally welcome are the materials associated with the conferences, projects or the institutions themselves" (Nielsen, 2017).

Zenodo applies the FAIR guiding principles for scientific data management and stewardship[6] by assuring that deposited content is "Findable, Accessible, Interoperable, and Reusable". The ESO Conference Proceedings 2.0 project provides compelling advantages as content submitted to Zenodo is:
- Citable — Zenodo will assign DOIs (Digital Object Identifiers[7]) to all submissions.
- Discoverable — content will be directly retrievable at Zenodo; more importantly, the ESO Library will notify ADS about the conference collection so that they can harvest the metadata and make them retrievable through the NASA ADS Abstract Service.
- Archived — Zenodo will permanently preserve the material.

In addition, the librarians create links between the ESO conference programme on the web and the Zenodo records. This enables easy retrieval of the presentation slides from the programme web page, and at the same time relieves ESO of the task of storing the final versions of presentation slides and posters on the ESO server.

In 2015, the ESO Library started to explain the benefits of Zenodo conference proceedings to organisers in order to find out whether there was any interest in the idea. The ESO/ESA workshop on Science Operations (SciOps) 2015 was the first trial, and a success. As a result, the presentation slides and posters are now easily retrievable and accessible (a) at Zenodo[8] (see Figure 1), (b) via the NASA ADS[9], and (c) through the ESO programme website (see the various links below[10,11]), and the content is permanently preserved.

As of mid-2018, the librarians have loaded 16 ESO-hosted conferences into Zenodo, providing lasting records of conferences held at ESO Garching and Chile.

Workflow at ESO

In order to establish a default procedure for ESO-hosted meetings, the Library has developed Conference Proceedings 2.0 at Zenodo. This is a workflow that is presented to the Chair of the Science

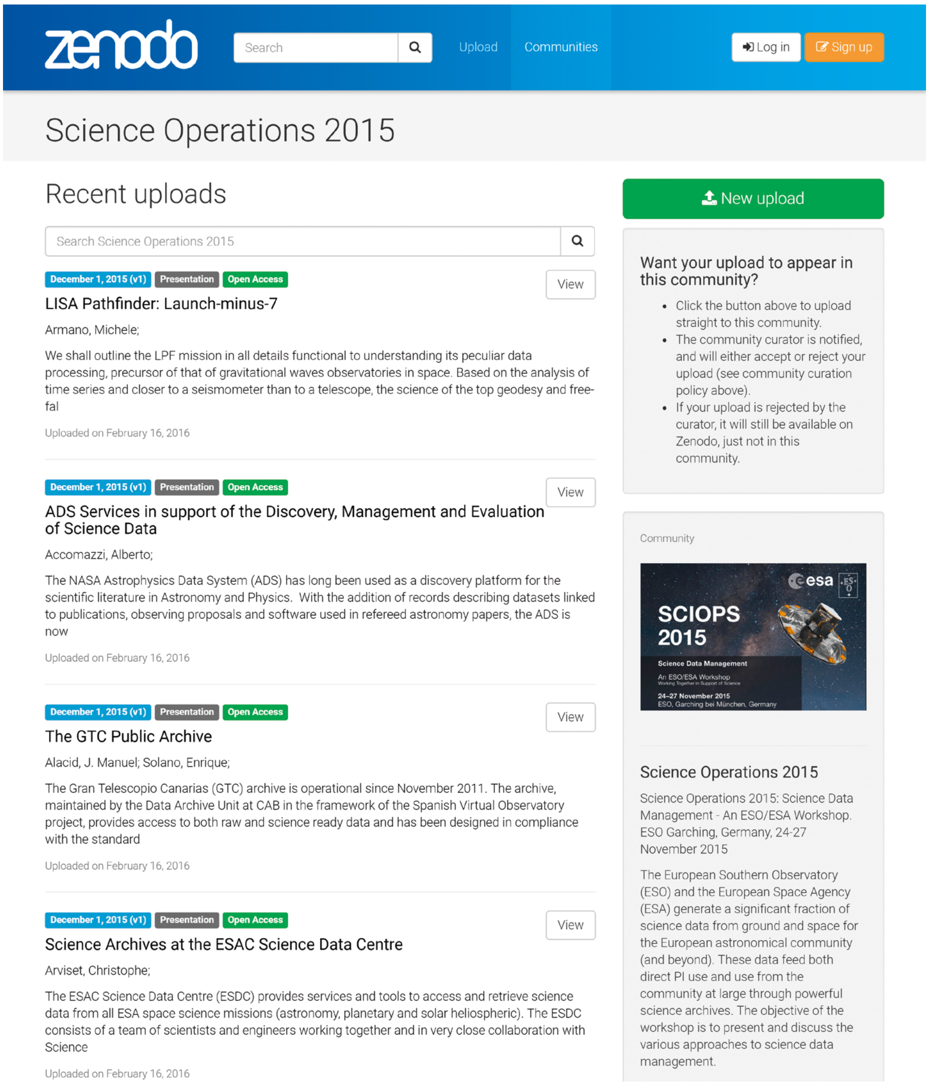

Figure 1. Screenshot of the Science Operations (SciOps) 2015 community at Zenodo, the first ESO Conference Proceedings 2.0 community that was curated by the ESO Library.

Organising Committee (SOC) as soon as an event is announced.

Well in advance of the conference, the organisers receive a Microsoft Excel template from the Library, prefilled with sample entries of the descriptive information (authors, affiliations, title, abstract, etc.) that is requested for each contribution. The Library also provides a sample email to the organisers that can be used to inform conference participants about the Zenodo proceedings. Either during or after the conference, the organisers fill out the Excel spreadsheet with metadata of all the records that will be submitted to Zenodo. Once complete, they return the file to the librarians, along with the PDFs of presentations and posters. Zenodo records can also be complemented with additional files, such as write-ups of discussion sessions or videos.

The ESO librarians add further metadata, for example, the conference name, location, and dates. In parallel, they prepare the respective conference area (called a community) at Zenodo where general information about the meeting can be displayed, along with a logo and a link to the conference website. Initially, the ESO librarians had to add each talk or poster manually to the newly created community space. In the meantime, Zenodo has made an application programming interface (API) available that can be used for bulk import. The Excel file along with the zipped PDFs are uploaded via a tool developed by the ESO librarians so that all Zenodo records pertaining to a given conference are created at once. During the upload a check for duplicates and missing information takes place. Once the quality check is successfully completed, all talks and posters are published at Zenodo by using an ESO-internal Zenodo interface created by the Library.

Zenodo encourages users to share their research as openly as possible to maximise use and reuse of research results. Therefore, the default license under which content is published is CC BY (current version: Creative Commons Attribution 4.0 International)[12]. CC BY 4.0 allows redistribution and reuse of a licensed work under the condition that the original creator is appropriately credited.

If a conference presenter is not comfortable with the CC BY approach, the uploaded content does not necessarily have to be open. Files can be embargoed or even defined to be private. In order to correct typos and other mistakes in the metadata, the librarians can modify the descriptions of records at any time. However, once a record has been published, the associated file cannot be deleted. If absolutely necessary, a revised version of the PDF can be uploaded; this will result in a new DOI for the record.

Should conference participants choose not to make their contributions available through Zenodo, they can opt out simply by informing the organisers.

If you are planning to organise a conference at ESO and would like to get further information about the Conference Proceedings at Zenodo, please do not hesitate to contact the librarians.

Conclusion

Organisers of ESO-hosted conferences increasingly use the library-developed Conference Proceedings 2.0 at Zenodo to establish citeable, retrievable, and permanently archived records of the meeting content. The effort required to gather the material and the respective metadata is reasonable, since authors do not need to spend additional time on writing a separate conference paper. With this Zenodo solution, presentation slides and posters presented at conferences are preserved and made available to the community promptly, in a professional way, and are available for reuse and redistribution by other researchers.

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Nielsen, L. H. 2017, DOI 10.5281/zenodo.802100

Links

1. Scanned versions of selected volumes of ESO Conference and Workshop Proceedings are accessible through the ESO Library catalogue: https://eso.koha-ptfs.eu/cgi-bin/koha/opac-search.pl?q=ccl=se%2Cphr%3A%22ESO%20Conference%20and%20Workshop%20Proceedings%22&offset=0&sort_by=pubdate_dsc
2. Papers published in ESO Conference and Workshop Proceedings are available at the NASA ADS: http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?sort=BIBCODE&bibstem=ESOC
3. ESO Astrophysics Symposia: https://link.springer.com/bookseries/3291
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7. DOI (Digital Object Identifiers): www.doi.org
8. SciOps 2015 conference proceedings accessible at Zenodo: https://zenodo.org/communities/sciops2015/
9. SciOps 2015 conference proceedings at ADS: http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?bibcode=2015scop.confE
10. SciOps 2015 conference ESO programme page presentations – click expand all to see DOIs linked to Zenodo: https://www.eso.org/sci/meetings/2015/SciOps2015/program.html
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Report on the ESO Workshop

A Revolution in Stellar Physics with Gaia and Large Surveys

held at the Warsaw University Library, Warsaw, Poland, 3–7 September 2018

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The exquisite astrometry and photometry of ESA's Gaia satellite combined with data from other large photometric, spectroscopic, and asteroseismic stellar surveys are enabling a revolution in our understanding of stellar physics. The goal of this workshop was to bring together a diverse community working on or making use of various aspects of stellar physics. The discussions covered both recent advances in the field and expectations for when new data and surveys become available.

Taking place a few months after the second data release (DR2) of Gaia, the workshop was ideally timed to allow the presentation of the first results to come out from those data. The topics covered included both theory and observations of: low- and high-mass stars; evolutionary stages ranging from the pre-main sequence to white dwarfs and black holes; stellar ages; stellar clusters; and stellar populations.

This workshop was co-organised by ESO and the Nicolaus Copernicus Astronomical Center, a research institute of the Polish Academy of Sciences. Poland became the 15th ESO member state in mid-2015. Hosting the workshop in Warsaw facilitated and encouraged the participation of the local community, helping to strengthen the links between Polish astronomers and the wider ESO community — of the 117 participants, 21 had Polish affiliation. The programme comprised 16 invited talks, 43 contributed talks and 40 posters. Details of the programme can be found via the workshop webpage[1]. Each talk was followed by a five-minute session dedicated to questions and discussions. It was very pleasing to note that the level of participation during these sessions was very high and that the number of questions was certainly above average. Poster viewing took place during all coffee breaks and was particularly encouraged during one dedicated long break of 50 minutes.

Setting the stage for the rest of the week, the first talk of the workshop was a review of Gaia DR2 by Elena Pancino. The talk highlighted the impressive numbers associated with Gaia, which includes positions and G magnitudes for more than 1.6×10^9 stars, astrometry and colours for more than 1.3×10^9 stars, radial velocities for more than 7×10^6 stars, and effective temperatures for more than 160×10^6 stars. At the faint end ($G > 14$ magnitudes), the astrometry of Gaia DR2 already reached the expected performance for the end of mission. The uncertainties and caveats associated with the released data were also discussed, stressing the need for users of Gaia data to familiarise themselves with the DR2 publications and documentation.

Stellar physics and models

Three invited talks reviewed the state-of-the-art stellar models, one focussing on low-mass stars, another on high-mass

stars, and the third on internal transport processes. Low-mass stellar models have many difficulties in accurately describing the pre-main sequence phase and the reasons are not entirely clear. Magnetic fields, starspots, problems with the description of convection and/or problems in the opacities all might play a role, and getting masses for more eclipsing binaries would help to disentangle these effects. For high-mass stellar models before the supernova stage, the main physical uncertainties include core overshooting, rotation, mass loss, and semi-convection. Mechanisms that transport chemicals inside stars, such as atomic diffusion, rotation, and thermoline mixing were also discussed, with particular emphasis on the impact of these processes on surface abundances used to study stellar populations.

The contributed talks in this session included the presentation of a new set of evolutionary tracks and isochrones from the PAdova and TRieste Stellar Evolution Code (PARSEC), computed with a new convective overshooting calibration which improves the position of the red giant branch bump in 47 Tuc. New empirical relations for the estimation of stellar masses and radii were presented. The relations which have a precision and accuracy better than 10%, were derived using data from asteroseismology, eclipsing binaries and interferometry. Another talk described an effort to improve the modelling of core-helium-burning stars combining different types of observational data with modern fluid-dynamics simulations in 3D. An effort to use eclipsing binaries to provide an improved calibration of convective overshooting, one of the major weaknesses in stellar models, was also presented.

From star formation to the main sequence

An invited talk summarised the impact of Gaia in the studies of star formation and pre-main sequence stars. Gaia data for stars in young clusters help to define cluster membership, to probe the internal kinematics of several clusters (revealing that some are expanding), and to study stellar and circumstellar properties. This is providing new insights into how star formation takes place and the evolution of discs and angular momentum in young stellar systems, as well as identification of eclipsing binaries in the Upper Sco star-forming cluster.

Contributed talks included a study of intermediate-mass pre-main sequence stars combining Gaia DR2 data with infrared photometry and spectroscopy. The differences in variability seen in Herbig Ae and Herbig Be systems suggest that the discs surrounding these stars have different properties. A series of contributions showed work that combines Gaia data with other photometric and spectroscopic surveys to study populations down to M stars for several star-forming regions, moving groups, and young open clusters. A careful analysis of the chemical composition of stars in the Pleiades suggests that inhomogeneities at the 0.04 dex level are present. It was suggested that these chemical differences might be related to planetary material being engulfed.

Figure 1. Workshop participants on the steps inside the impressive Warsaw University Library.

Post-main sequence evolution

One invited talk covered the asymptotic giant branch (AGB) and post-AGB phases of low- and intermediate-mass stars. Besides the complexities typical of these stages (for example, thermal pulses and envelope ejection), the models inherit the uncertainties from the earlier phases (regarding, for example, rotation, deep mixing and magnetic fields). Gaia itself has had little impact on these stars so far, but the Atacama Large Millimeter/submillimeter Array (ALMA) has been particularly important in unveiling their circumstellar environments.

Another invited talk covered the white dwarf stage. Important progress in this field came with SDSS but Gaia DR2 has now increased the sample of known white dwarfs. White dwarf main sequence binary systems are particularly valuable as the age can be derived from the white dwarf while metallicity can be measured in the MS star companion. Some of these objects show signs of accretion of planetary material in their atmospheres, opening a window to studying the chemical composition of this material. Objects that might have survived a SNIa explosion have also been identified, giving some unique insight into these rare events. Future massive spectroscopic surveys will play an important role in advancing the field.

Contributed talks included: the report of 300 new red-clump Li-rich giants identified from spectra obtained with the Large sky Area Multi-Object fibre Spectroscopic Telescope (LAMOST); a chemical analysis of intrinsic and extrinsic S-type stars with precise positions in the Hertzsprung Russell (HR) diagram thanks to Gaia parallaxes; the presentation of a new catalogue of ~ 260 000 high-confidence white dwarfs identified with Gaia data; and the search for stellar-mass black holes using microlensing with OGLE and Gaia data. Recent progress in understanding the nature of sub-dwarf A-type stars was also presented. Some of these objects seem to be old, metal-poor halo objects, others are extremely low mass white dwarfs, but the nature of many of these objects remains a mystery.

Surveys and techniques

An invited talk reviewed the power of asteroseismology in probing stellar physics, highlighting important results such as the discovery of constant core rotation in red giants. Synergies between Gaia and asteroseismology were discussed and the need for interferometry to provide accurate stellar temperatures was stressed. This will bring further progress not only in the study of stellar physics but also in the field of exoplanets. Another invited talk highlighted the opportunities that stem from combining photometric surveys with Gaia data. They include the unveiling of new physics using calibrated colour-magnitude diagrams (CMD) for large stellar samples and time domain studies, which are important, for example, for the understanding of the evolution of stellar rotation. The Large Synoptic Survey Telescope (LSST) will expand these opportunities in the future.

On the spectroscopic side, one invited talk presented a summary of three high-resolution large surveys: the Apache Point Observatory Galactic Evolution Experiment (APOGEE); Gaia-ESO; and Galactic Archaeology with HERMES (GALAH). Surveys such as these are providing chemical abundances that are important data for stellar physics studies. Another invited talk discussed recent progress in modelling stellar photospheres, which are important tools for the determination of chemical abundances. Results based on 3D non-local thermodynamic equilibrium (NLTE) models suggest changes in abundances that might significantly impact our understanding of stellar physics and stellar populations.

Contributed talks included a study of the rotation curve of the Milky Way and the description of a search for extremely metal-poor stars with the Pristine photometric survey and Gaia. Follow-up spectroscopy has revealed a high efficiency in identifying stars with [Fe/H] < −3.0 dex. Such stars offer an opportunity to study early star formation and the first supernovae. Another talk presented a study of spectroscopic and astrometric radial velocities (RVs) using stars in the Hyades. The study demonstrates that spectroscopic RVs with accuracy of 20–30 m s^{-1} are possible. Moreover, the internal velocity dispersion of the cluster, the rotation gradient and the gravitational redshift have been determined.

Binaries and multiple stars

An invited talk reviewed the evolution of stellar binaries and triples, focusing on the comparison between observed properties and models that take into account stellar interaction. Unstable mass transfer in common-envelope evolution is an important source of uncertainties in binary evolution. Gaia will be important in extending the size of the samples available for study. It was stressed that the evolution of stars in triple systems enhances the occurrence rate of mass transfer, the merger rate of compact objects, and the formation of compact binaries.

One contributed talk discussed cataclysmic variables and how Gaia is helping to constrain the surface gravity of the white dwarf companions and their space density. Another talk discussed the discrepancy between evolutionary, spectroscopic, and dynamical mass estimates, stressing the need to combine multiple observables in solving the problem. A discussion of the properties of short-period binaries identified in the GALAH survey was also presented.

Another talk presented a study of binary disruption that shows that, in most cases, the ejected star moves slowly. The observed runaway fraction of O-type stars exceeds by a factor of 10 that predicted by models. On a similar topic, another talk discussed how Gaia is helping to exclude and select between the likely ejection mechanisms that can explain the presence of hypervelocity stars. The detection of spectroscopic binaries in the Gaia-ESO Survey was also presented, confirming that the frequency of single-lined binaries (SB1) decreases with metallicity and that the frequency of both single- and double-lined binaries (SB2) increases with spectral type. Hot subdwarfs were discussed in another talk, a field where Gaia is helping with the identification of large volume-limited samples and with parallaxes to constrain the stellar masses.

Stellar variability

One invited talk highlighted the impact of Gaia on variability studies. Gaia is repeatedly scanning the sky over many years and providing nearly simultaneous photometry and spectroscopy for all the different types of variable stars. With Gaia data it is possible to position these stars accurately in the HR diagram and to add to that the time axis, allowing the observation of how the pulsating stars move in the diagram through their variability cycles.

Another invited talk described mainly the results of the Optical Gravitational Lensing Experiment (OGLE), a time domain survey aiming to identify microlensing events that also provides light curves for billion of stars. Amongst other achievements, OGLE has discovered extrasolar planets and new types of variables like blue large-amplitude pulsators. The observed fields include the Galactic disc and bulge as well as the Magellanic Clouds. Other surveys like the All Sky Automated Survey (ASAS), BRIght Target Explorer (BRITE), Solaris and Pi of the Sky were also mentioned.

A series of contributed talks discussed Cepheids. Discussions included the use of Cepheids as standard candles, their use in constraining models of the evolution of intermediate-mass stars, and how measuring masses of Cepheids in binary systems is important to constrain period-mass-radius relations. Another contributed talk described the use of Cepheids and RR Lyrae observed with OGLE to study the structure of the Magellanic Clouds. These stellar tracers suggest no evident connection between the clouds. A discussion of dynamical phenomena in RR Lyrae using K2 light curves was also presented, revealing how Gaia DR2 has enabled the discovery of many more RR Lyrae systems in the original Kepler field. Another talk presented the combination of the ASAS-SN photometric survey with APOGEE spectroscopy to study variable stars.

Stellar ages

An invited talk described the determination of stellar ages using stellar models and colour-magnitude diagrams from Gaia. General applications to pre-main sequence stars, open clusters, and single stars were also discussed and the need to use robust statistical techniques was highlighted. Models do not always fit the observations, which emphasises that there is missing physics in the models, particularly for M stars. A lack of metallicity and extinction measurements can also limit the accuracy of the results themselves, particularly in star forming regions.

Contributed talks included a report on the determination of ages for the Gaia benchmark stars, a series of stars used as references for Gaia and many spectroscopic surveys. Gyrochronology was discussed in another talk where new models that take into account magnetism and stellar winds were described. The lack of — and need for — information on slowly rotating old M stars was highlighted. Gaia is providing crucial data on cluster membership, masses, absolute magnitudes, and rotation periods that are going to help gyrochronology to improve the accuracy of stellar age estimates.

The use of chemical abundance ratios as stellar clocks was discussed in one talk. A Bayesian tool called the Unified tool to estimate Distances, Ages and Masses (of stars) (UniDAM) was the topic of another talk. This tool has been used to provide ages for about 5.5×10^6 stars observed by many spectroscopic surveys. One talk presented the combined use of Gaia and LAMOST to derive ages to be used in studies of Galactic archaeology.

Stellar populations

An invited talk discussed the needs of Galactic archaeology in terms of reliable ages, which are needed to complement information on chemistry, masses, and evolutionary stages coming from spectroscopic and asteroseismic surveys. It was stressed that, for giants in particular, isochrone fitting is the main way to obtain ages but that models suffer from key uncertainties. Significant improvements are coming from the study of the secondary red clump in clusters, as well as double-lined eclipsing binaries, and from asteroseismic data.

Galactic archaeology using spectroscopic surveys like APOGEE, the Gaia-ESO Public Spectroscopic Survey and GALAH, were discussed in a series of talks, also including smaller samples of stars. The topics covered the understanding of the disc populations, radial and vertical gradients, and the evolution of metallicity and other chemical abundances with time. The use of Gaia parallaxes to improve spectroscopic analysis in the context of the GALAH survey was discussed in another talk. The last talk discussed Galactic chemical evolution models and their comparison with abundances from the APOGEE and the AMBRE project.

Several themes recurred throughout the workshop, including the need to combine several types of data to uncover the limitations of current stellar models. The requirement for higher quality chemical abundances from spectroscopic surveys was also stressed many times. The community is working hard to use the data that are currently available but it is also looking forward to future Gaia data releases, new missions like NASA's Transiting Exoplanet Survey Satellite (TESS) and LSST, and new massive spectroscopic surveys like the 4-metre Multi-Object Spectrograph Telescope (4MOST) and the WHT Enhanced Area Velocity Explorer (WEAVE). It is an exciting era for studies of stellar physics, and many participants already expressed the wish to meet again for a similar workshop after the release of Gaia DR3.

Demographics

The gender balance among the speakers reflected the 1:3 (female:male) distribution of the participants, though the SOC had a corresponding ratio of 4:7 (female:male). The speakers constituted a mix of early career researchers (students and postdocs) as well as more senior staff.

Acknowledgements

We thank ESO for financial support and for the opportunity to host the workshop in Poland. We would like to thank the LOC, the SOC, and the session chairs for all their help before and during the workshop. We are also grateful to the administrative staff of the Nicolaus Copernicus Astronomical Center for their support with the organisation of the event.

Links

[1] The workshop webpage includes links to the presentations that speakers have uploaded: https://indico.camk.edu.pl/e/revolution

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Report on the ESO Workshop

Take a Closer Look: The Innermost Region of Protoplanetary Discs and its Connection to the Origin of Planets

held at ESO Headquarters, Garching, Germany, 15–19 October 2018

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About 150 scientists from all over the world convened at the ESO Headquarters to discuss the origin of close-in exoplanets and the properties of the inner regions of protoplanetary discs, where these planets are formed. In a cordial atmosphere, made possible by the collaborative attitude of the very diverse group of attendees, the discussion led to a deeper appreciation of the importance of several observing techniques and of advances in modelling to tackle key open questions. In addition, the participants had the chance to experience a special show at the ESO Supernova Planetarium & Visitor Centre, which highlighted the potential of this facility.

Motivations for the workshop

Radial velocity and transit surveys have discovered an impressive population of close-in exoplanets, but their origin remains unclear. What are the physical and chemical conditions of protoplanetary discs that foster the formation of close-in planets? How are close-in planets related to the inner disc and how can we observe these regions of the disc? How are inner and outer discs connected and what mechanisms drive their evolution?

We now have solid evidence for the existence of a large population of exoplanetary systems, some of which comprise several planets very close to the central star, i.e. at distances of 0.1–1 astronomical units (au), even around late-type pre-main sequence stars that are younger than 5 Myr (called T Tauri stars). These planets are usually slightly bigger than the Earth and can reach the size of Neptune, while Jupiter analogues are rarer. This finding differs from what we observe in our own Solar System and raises the question of how such planets form. From a theoretical point of view, it is still challenging to show that these planets formed in situ, but it is similarly difficult to explain this population of close-in planets as the result of migration through the disc.

Figure 1. The conference poster.

To advance our understanding of the formation and migration mechanisms of these planets, it is crucial to know the conditions within the inner parts of their progenitor protoplanetary discs. The innermost disc region is where most of the processes related to star-disc interaction take place. The magnetic field of the central star truncates the disc at a few stellar radii and channels material onto the central star. Magnetic fields also drive the ejection of fast-collimated jets and slow winds. Also, the inner disc region undergoes rapid evolution, as evidenced, for example, by both short and long-lasting dimming events. This rapid evolution is likely to impact the formation of planets. Finally, a fraction of discs known as transition discs show a deficit of dust in the inner few au of the disc, which could be related to the mechanisms driving disc evolution in this planet-forming region.

Studies of this key disc region require innovative techniques and a wide range of instrumentation, because radio interferometers, typically used for disc studies, cannot resolve spatial scales smaller than ~ 10 au in most discs. New observations

Figure 2. The conference workshop photograph.

with instruments on the ESO Very Large Telescope (VLT) and the Very Large Telescope Interferometer (VLTI), as well as with other telescopes and radio interferometers, provide us with unprecedented information probing a range of scales relevant to disc evolution and it was this that motivated this workshop (Figure 1). Specifically, this workshop was convened to discuss the current knowledge of: the morphology and composition of the innermost regions of the disc; the star-disc interaction processes; the theories to describe the inner disc evolution; and the formation of close-in planets.

The workshop programme

With these themes defined, the workshop was aimed at scientists working on a number of related topics, including developing planet formation models, performing observations of exoplanets and discs, and working on current and future high-resolution instrumentations. With 150 participants (see Figure 2), 15 invited talks and reviews, 40 contributed talks, and about 70 posters, the workshop hosted a sizeable fraction of the target community[1]. In order to facilitate discussions, we decided to have contributed talks of 15 minutes, followed by five minutes for questions. This was generally found to be a good balance between space for new results and time for follow up questions; it also ensured keeping to schedule. Each session included two invited review talks, one from a theoretical and one from an observational perspective. Four additional invited talks were focused on current and future high-resolution facilities.

Furthermore, we had two dedicated poster sessions that were well attended, with lively discussions. Poster presenters were each asked to provide a single-page PDF slide to promote their main result. These were used to create a slideshow that was shown during the breaks in the main auditorium. Finally, a panel of four judges selected three outstanding posters, one of which was named the "best poster"; all three authors were given prizes from the ESO shop and their posters were further advertised in the auditorium during breaks on the last day.

A time-slot on Thursday was reserved for special breakout sessions, to allow discussions on particular subjects that may not have been equally relevant to all participants. The main breakout session in the auditorium dealt with a peculiar object, RW Aur. This session consisted of five highly focused five-minute talks which briefly presented recent results, followed by a lively and wide-ranging discussion lasting for more than an hour. This allowed everyone working on this target to get acquainted with the latest results from other groups, and to explore the possible explanations fitting the wealth of observational and theoretical constraints. A parallel session in the Pavo Room was organised by Mihkel Kama on observations of the inner regions of Herbig Ae/Be star discs, and this was also very well attended. Lastly, a group of colleagues took advantage of being together to discuss the reduction and analysis of still proprietary data from GRAVITY, the second-generation VLTI instrument.

The workshop closed with a final discussion led by four Science Organising Committee (SOC) members based on anonymous questions put into a "Magic Box" (Figure 3) by the participants during the week. This allowed more participants to ask any big questions, including questions they may not have had the courage to ask during the workshop. Indeed, several Magic Box questions turned out to be tricky and even provocative (in the most positive sense). The resulting lively discussion revealed a large variety of opinions and constructive answers.

All talks and posters are available via the Zenodo platform[2], where they will be stored and assigned a Digital Object Identifier (DOI). In the following sections, we summarise the subject matter of the workshop, broadly following the various programme sessions.

Exoplanet detection and formation mechanisms

As described in the review by Raphaëlle Haywood, the large number of close-in exoplanets detected to date gives us the possibility to explore the observed lack of planets at orbital periods shorter than ~ 3 days and with sizes ~ 2 $R_\oplus$. It is now possible to try to reproduce these observations with different formation mechanisms, for example based on different chemical properties of the host star, or as the result of the evolution of planetary atmospheres due to photoevaporation driven by ultraviolet radiation coming from their host stars. The latter model seems to explain most of the observations, in particular the "evaporation valley" — a gap in the distribution of planets with sizes of between 1.5 and 2.0 $R_\oplus$. One of the major open issues in this quest is the determination of the masses of these planets, in particular below ~ 2 $M_\oplus$. In this mass range, the magnetic activity of the host star and its rotational modulation contribute a radial velocity signature that has a larger amplitude than the effect due to the planet. A lot of effort is being invested into disentangling these effects; approaches include precisely modelling the physical processes causing the stellar contributions to radial velocity variability — for example, by viewing the Sun as a star — or accounting for these effects by applying robust statistical techniques to well monitored radial velocity time series.

On the other hand, the search for the youngest exoplanets is even more challenging. Radial velocity signatures from stellar magnetic activity are even more

Figure 3. This is the "Magic Box" in which participants could confidentially post their most burning questions over the duration of the workshop. These questions were used to drive the discussion on the last day of the workshop.

pronounced in young stars, as discussed later in the workshop by Gaitee Hussain and Colin Hill. Direct imaging also remains challenging. While the recent discovery of a planetary-mass object in the disc of PDS 70 was reported in a talk by Miriam Keppler, the lack of Hα emission at the location of the claimed planet in the disc of another system LkCa 15 (shown by Ignacio Mendigutía) casts doubts on its existence and highlights the need for careful characterisation and long-term monitoring of these candidate planets. Furthermore, Luca Ricci showed high-resolution ALMA observations of protoplanetary discs, which reveal a large number of gaps and rings (also see p. 19). If these structures are caused by exoplanets, they imply planetary masses smaller than the minimum detectable by current direct imaging instruments. Once those planets are identified, VLTI data provide a new way of retrieving their spectra, as shown by Karine Perraut for β Pic b.

Owing to the difficulty of detecting young exoplanets, the main formation mechanism remains unclear. In his review talk, Chris Ormel reported that there are three main theoretical scenarios that aim to describe the formation of these planets: "in-situ" formation; formation in the outer disc followed by inward migration; and a pebble-driven formation and migration scenario. In the current assessment there are some problematic aspects in all the scenarios under consideration, for example, regarding efficiencies (which can be either too high or too low), and regarding the final composition of the planets. Many of these issues, and some alternative scenarios, were addressed in several theoretical contributed talks on this topic, but it was broadly highlighted that better information on the precise morphology, chemical properties, and evolution mechanisms of discs is necessary to constrain such models.

Morphology of the inner disc

The theoretical review by Stefano Facchini, the observational review by Stefan Kraus, and the invited talk by Andrea Banzatti all presented evidence for the rapidly evolving inner regions of protoplanetary discs; this is challenging to observe directly and to describe via theoretical models. A particularly striking new result is the evidence from spectroscopy (mainly from the ultraviolet and infrared), from near-infrared interferometry, and from scattered light observations, that many discs appear to have a misalignment between the inner and the outer disc. In extreme cases the inner disc can be close to edge-on, whereas the outer disc is almost face-on. Systems known to have dips in their light curves, possibly caused by extended disc material close to the star, are observed with a range of different inclinations of the outer disc. Megan Ansdell and Paola Pinilla discussed how some of these "dipping" stars have shadows that appear to be cast by the inner disc onto the outer disc. Megan Ansdell cautioned that non-accreting systems could also have "dipper" lightcurves, so a number of mechanisms may be responsible for the "dipping" observational phenomena.

From this point of view, it is crucial to model what can cause misalignments between the inner and outer discs. The effects of binaries and of misaligned planets are being studied, as shown by Stefano Facchini, Rebecca Nealon and Hossam Aly, but other processes can also play a role. In the breakout session about the peculiar dipping star RW Aur, there was extensive discussion of the idea that winds arising from the inner disc regions could lift dust and cause dips as well as explaining other observables, for example, an increase in polarisation and the emission of strong iron lines in the X-ray regime. Whether this process could happen in other objects and somehow mimic the effects of a misaligned inner disc has yet to be understood.

Evolution of the inner disc

The question arises of what processes cause the rapid evolution of the inner disc. For a few years there has been a growing consensus that magnetically induced winds can be responsible for the observed evolution of discs (as described by Giovanni Rosotti in his review talk, and by Jake Simon). However, to constrain mechanisms such as this, further effort must be invested into understanding the properties of the gas in the inner disc regions and of the related interaction between the disc and the star. A number of observing campaigns have been planned to tackle this problem, bringing together complementary techniques, such as mapping the stellar magnetic field and tracing the accretion geometry, while simultaneously intensively monitoring lightcurve variability (as discussed during talks by Paola Pinilla and Silvia Alencar).

From an observational point of view, it is currently possible to probe the properties of the gas in the inner au or so only with spectroscopy, mainly in the infrared, as shown by Melissa McClure and Andrea Banzatti, or by observing the accretion process. Indeed, Laura Venuti explained in her review talk that current data can place strong constraints on the evolution of the accretion processes in time, on both short and secular timescales. Moreover, Rebecca García López discussed how near-infrared interferometric observations of possible tracers of accretion (for example, Brγ) could constrain the emitting regions of the line, and thus the origin in either accretion stream or winds. The modelling of these observables is still under way, mainly from the wind/outflows perspective, as discussed by Somayeh Sheikhnezami.

The inner disc is evolving both physically and chemically. In particular, Arthur Bosman and Richard Booth showed how chemical tracers and metallicity in the very inner disc could be used to help constrain the radial transport of both gas and solids in protoplanetary discs. The need for more sophisticated (in particular 2D) models was clearly highlighted.

Main conclusions and ways forward

This workshop demonstrated spectacularly how our knowledge of the properties of the inner disc is currently evolving from a picture of a quasi-static environment to one of a highly dynamic region, with rapid changes in morphology, chemical composition, and emission properties. In this context, the workshop revealed an impressive wealth of diagnostic methods encompassing X-ray, ultraviolet, optical, infrared, millimetre and even centimetre, wavelengths — with the need for multi-wavelength observations increasingly being recognised by the community.

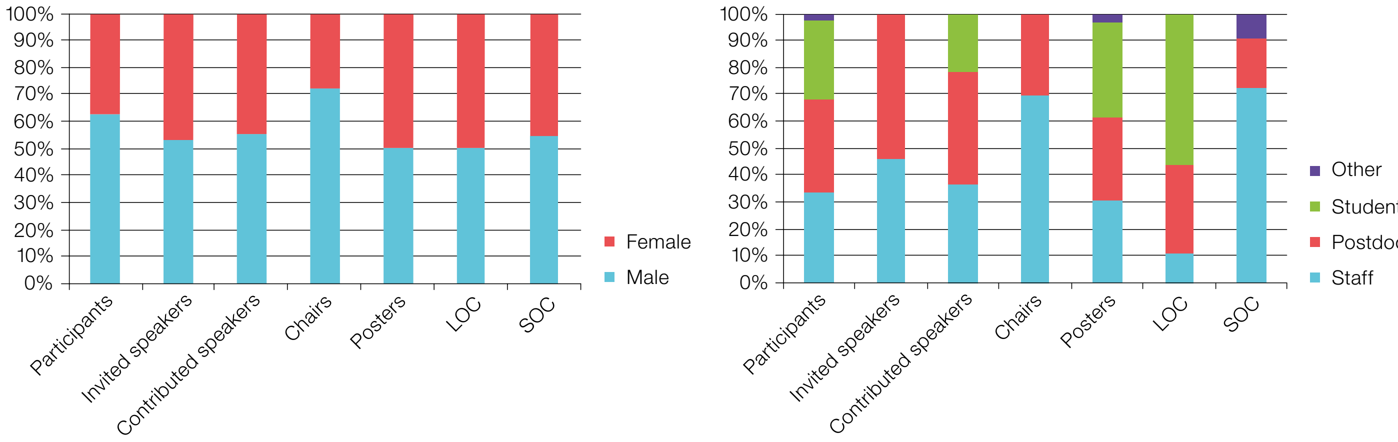

Figure 4. This shows how the distribution of the gender and career level of the participants compared with the corresponding distribution of speakers and organisers.

We also saw an equally impressive rate of progress in the theoretical understanding of the evolution and properties of discs. These models must contend with a wealth of new observational constraints that are continuously coming in. It is now evident that static models need to be replaced by dynamic ones, which include magnetic fields and disc misalignment. These should provide clearer observational predictions to further guide the efforts of observers, ultimately leading to planet formation theories stringently constrained by observations.

The dedication and constructiveness showcased at this workshop prove that the community is clearly ready for this challenge. The diverse audience included many early career scientists, clearly demonstrating the growing nature of this field and the intense interest in the inner regions of protoplanetary discs, their evolution and the role they play in planet formation. During this timely workshop, it also became clear that ESO is providing the current and future instrumentation that will help scientists stay at the forefront of this study for some time to come.

Demographics

Our workshop was organised with the goal of being inclusive and encouraging as diverse an audience as possible to attend. In order to limit the amount of weekend travel — at least for European participants — the workshop started on Monday after lunch and finished at lunchtime on Friday. The Local Organising Committee (LOC) also organised child care in the ESO child-parent room for the children of two participants, who could then attend the whole workshop. The costs of this service were also partially covered by the workshop funds. The workshop funds also covered the costs of lodging for four participants and provided financial support to ten participants.

The selection of SOC members and, in turn, of invited speakers was based solely on scientific merit and the relevance of the research activity for the workshop. The SOC comprised six male and five female scientists. Also, the selection of invited and contributed talks based on scientific excellence resulted naturally in an even gender balance (see Figure 4), demonstrating their success in overcoming unconscious biases.

For our workshop, we were keen to quantitatively evaluate the distribution of participants, both in terms of gender and career stage. In order to monitor this, we requested permission from participants to collect the corresponding information; the response was extremely positive and the results are shown in Figure 4. These confirm a good gender balance amongst the speakers, and amongst the participants overall, suggesting that this research area has close to an even gender balance. The "academic age" distribution of the invited and contributed speakers was also aimed at promoting the work of early-career scientists, with about 40% of the talks given by staff in tenured or tenure-track positions, about 50% of the invited talks given by post-doctoral scientists, and 20% of contributed talks given by PhD students. These statistics further underline what was generally noted during the workshop — that the diversity of the participants and the efforts made by the organising committees to ensure everyone was encouraged to actively participate both helped to drive engaging discussions, and to provide a platform on which to build future productive collaborations.

Acknowledgements

The organisers are very grateful to ESO for providing support with both funding and logistics. In particular, we would like to acknowledge the invaluable time and effort invested by our colleague Stella Chasiotis-Klingner with helping to set up and run the workshop itself. The members of the Science and Local Organising committees are warmly thanked, the former for their expertise in devising an excellent science programme, and the latter for their excellent ideas ensuring maximum participation and the smooth running of the workshop itself. The judges for the poster prizes are gratefully acknowledged for giving up time during the poster sessions to judge the many excellent posters. Thanks also to Luis Calçada for the workshop photo. The ESO Supernova coordinator, Tania Johnston, arranged a spectacular planetarium show that was greatly enjoyed. Many thanks also to the librarians for helping us publish the excellent posters and talks via Zenodo.

Links

[1] The workshop programme: https://www.eso.org/sci/meetings/2018/tcl2018/program.html
[2] Zenodo link: https://zenodo.org/communities/tcl2018/

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Fellows at ESO

Chian-Chou Chen

Chian-Chou Chen

彗星, a book about comets first attracted me to astronomy. It was on a shelf in a seemingly unremarkable bookstore surrounded by food vendors in a typical night market in Taichung in Taiwan. At first I was enjoying the fried chicken and bubble milk tea more as I casually flipped through the book. After a few pages, I put aside my food, sat down, and finished the whole book. Despite the hot summer the book gave me goose bumps, with fascinating photos and mysterious facts, describing this thing that is flying across the Universe, a concept that effectively blew my mind.

Despite being inspired by a book, I was in fact a wild child with no interest in reading. If anything, it was thanks to my father that I would read about physics. For example, books by Richard Feynman got me thinking about things like angular momentum before it was taught in school. The black holes that appear in Stephen Hawking's books would get me thinking about space and time the whole day. My father would tell me about Einstein's theories of relativity and we would both be overwhelmed by the concept of converting mass into energy.

I was fortunate enough to carry on my passion about physics during undergraduate studies, at which time I got into the summer research programme offered by the Academia Sinica Institute of Astronomy and Astrophysics in Taipei. During those two months, I worked on my first ever project about astrophysics, using the SubMillimeter Array (SMA) to study the molecular gas and dust around protostars. I reduced the data, analysed the results, made plots, and presented a poster at a local conference. In hindsight, that summer programme was extremely valuable, allowing me a first taste of being a real astronomer, and I liked it.

After undergraduate studies, I entered the military, as a result of mandatory public service in Taiwan. Because it is public service, I got to meet people from a variety of backgrounds, whom I would probably never have had a chance to meet had I not joined the military. We would talk about our lives and the plans for the future, and during this time – effectively a gap year – I became motivated to apply for PhD programmes in the USA, which unlike European ones do not need a master's degree. After a huge amount of work putting in applications, an acceptance email from the University of Hawaii came out of the blue during the Chinese New Year in 2008. I was dancing with my mother, picturing what life ought to be in the next five years in the island paradise.

Besides regular courses, in order to help with the search for ideas for PhD topics, the university requires students to undertake two one-year research projects in the first two years of the PhD; these two projects can cover vastly different topics. I carried out my first graduate research project with Jonathan Williams, making good use of my knowledge and skills about the SMA and protostars, which eventually led to one of my first publications. For the second project, I was eyeing something completely different, involving larger physical scales: galaxies, galaxy clusters, and cosmology. During that time I was taking a course with Len Cowie about these topics, and thought why not combine my skills in the submillimetre with galaxies. Fortunately, Len happened to have a project on exactly that idea at the same time, and after a few chats we decided to team up, along with Amy Barger and Wei-Hao Wang — close collaborators of Len — to work on my second graduate project; the starting point of my now decade-long research career on the submillimetre galaxies. It in the end it went so well that we published the results not long after the end of the second year.

What came after the end of the second project was also the good news about the commissioning of the new submillimetre camera, SCUBA-2, mounted on the James Clerk Maxwell Telescope (JCMT). The community at that time had long been waiting for this revolutionary camera to survey the submillimetre sky at an unprecedented speed. Given the timing, it seemed natural to work with Len on a PhD topic about submillimetre galaxies using SCUBA-2. On the other hand, I realised that It could be risky to rely on a new instrument for the whole PhD, so I decided to use SCUBA-2 for only half of my thesis, and designed the other half involving the SMA, the facility that I knew well and that was working. Luckily, with the invaluable help of Len and Amy, both halves worked well and the thesis was successful.

My skills and first-hand experience with SCUBA-2 led me to my first postdoc at Durham University in the UK, working with Ian Smail on ambitious SCUBA-2 legacy surveys and various follow-up programmes using the Atacama Large Millimeter/submillimeter Array (ALMA) and ESO's Very Large Telescope (VLT). During this time I also had the freedom to explore and build up my own research projects, moving towards becoming a completely independent researcher. It was not easy, and most proposals failed. It was when these failures happened that I really appreciated working in a well-established group, with many other projects that are also worth pursuing; mitigating the possible damage from these failures to one's career. Luckily after many tries I started to slowly build up a research programme, at which time Ian suggested the ESO fellowship.

The offer from ESO came rather early, an excellent gift for Christmas. After some serious discussions with my partner we decided to take our newborn child to Germany — a country where I had lived, for a brief period of time, when I was five. Despite that, at first we worried that life could be a bit difficult since we don't speak the language, but the idea of having complete freedom to do research in Munich overcame that worry. In hindsight, coming to ESO was perhaps one of the best decisions I've ever made. The vibrant atmosphere of the research environment at ESO constantly fosters new projects and collaborations. The logistical support that ESO provides, in particular for people with small children, is unparalleled. Perhaps most importantly, the goodwill from people to make ESO a better working place can be seen in almost every corner. Overall, it has been eye-opening for me personally to experience such a motivational environment, and I will for sure bring these values to wherever I go for the next step of my career.

Alexandre Gallenne

I was not dedicated to being an astronomer, or even a scientist. But at one point in my life I was looking for something exciting, interesting, and more importantly — to do work I really like. Now here I am, working at the most productive worldwide observatory, and operating the most advanced instruments and telescopes. Here is my story.

I spent my childhood in the Normandy countryside, in the northwest of France, and this is where my passion for amateur astronomy began. The countryside is an amazing place as it is free of light pollution, giving access to astonishing night skies. Lying down in the grass near a lake, listening to singing frogs; this is how I started becoming a stargazer, watching the moving celestial sphere, the brightest planets and our Milky Way rising over the horizon. However, at that time I was not thinking of studying celestial bodies — I was just a dreamer, amazed in the face of the Universe.

I had a normal high school education, not really oriented towards continuing on to university, but rather aiming for a professional degree so that I could start working as soon as possible. I actually did not really like studying and I wanted to escape it as soon as I could. After my high school degree, I started working as an electrical engineer for various companies. Although it was quite interesting, I did not really like it, and I did not see myself doing that kind of job all my life. So I started to look for other interesting things to do. I tried to join the Air Force, via a three-day test to become a fighter pilot, but I failed during the second day. I then went to the army to be a paratrooper; however I quickly realised that such a life was not for me. Fortunately, a

Alexandre Gallenne

few days before leaving the army, something triggered in my brain while I was alone in the dormitory looking through an astronomy magazine. I actually do not remember exactly what happened, but this was the moment I decided to start to study again, with the goal of becoming an astronomer.

I gathered a lot of information on how to reach that goal, and I realised that this was a long-term objective, with at least eight years of study, requiring patience, motivation and determination. But this did not scare me. I had to leave the countryside for the nearest big city and spent two years at University of Rouen starting to learn general physics. However, once I became aware that the university did not specialise in astrophysics, I moved to the capital, to one of the best universities in Europe specialising in science and medicine, called Pierre & Marie Curie University or Paris VI. There I studied fundamental physics, astronomy and astrophysics and after a few years I obtained my master's degree. It was a long and hard road to the degree because such a high level of study requires time and lot of effort.

It was almost the end of the road; I was about to start a PhD, which is actually where you really start investigating and learning how to become a researcher. The choice of PhD project is very important as, for most of us, it determines our future field of research. In my case, my PhD topic was influenced by my master's thesis. Before starting my PhD, I spent three months at the Observatoire de Paris for my end of year master's project. I worked under the supervision of Pierre Kervella with MID-infrared Interferometric instrument (MIDI) data, an ESO first-generation interferometric instrument. The topic of this master's thesis was to spatially detect nearby infrared emission around Cepheid stars, caused by possible circumstellar envelopes.

This work was really exploratory, as we did not know anything about these envelopes, which had only recently been discovered. I reduced and analysed the MIDI data for two Cepheids, which resulted in the detection of nearby warm infrared emission. This work led to a scientific refereed publication, to which I am proud to have contributed. During this project, my supervisor asked me if I would be willing to continue this exploratory work on circumstellar envelopes of Cepheids for a PhD, and I obviously accepted. As part of this PhD, he also asked if I would be interested in applying for an ESO studentship programme and going to Chile for two years. This was a hard choice to make as going to a new country meant that I would have to deal with a different culture, language, money and have a different way of life without my family and friends. This was not like going to Spain or England because Chile is 12 000 km from France, so it was not possible to come back for the weekend. It had been a long time since I decided to start studying again, but I was still determined and motivated so I saw this opportunity as a new adventure that could only be of benefit to me. When ESO awarded me the studentship, I was obviously happy, but also anxious at the thought of starting a new and completely different life.

At ESO, I was co-supervised by Antoine Mérand, an ESO staff astronomer. These two years of my PhD resulted in one of the best parts of my personal and professional life. I met a lot of people; some are now friends, while others became collaborators. This studentship enabled me to be in direct contact with an operational observatory, its instrumentation, and to collaborate closely with astronomers across various fields of research. This work in an international environment provided a great experience at the most productive ground-based astronomical observatory in the world. Unfortunately, everything has to end, and after two years I had to come back to France to finish my PhD. Nine years have passed since I took the decision to study astronomy. This long journey led me to obtain a PhD and I was now an astronomer.

However, all this was the "easy" part. I then had to find a postdoctoral position, and maybe after some years, a permanent job in a University, research institute or observatory. Because of the strong links I have with this country, I came back to Chile for a postdoctoral position at Universidad de Concepción, in the group under Wolfgang Gieren, a recognised expert in the field of Cepheids and the distance scale. This position allowed me to become a mature and independent astronomer, create new collaborations (and friends), and start new research projects. After about three years in Concepción, it was time to look for a job again. An astronomer job is quite precarious, and you can spend years looking for a permanent position — if you are lucky enough to get one.

After Concepción, I was awarded a four-year ESO Fellowship. Here I am now, an astronomer at the Very Large Telescope Interferometer (VLTI), the interferometric part of the ESO Paranal Observatory. As a fellow, I am part of the Science Operations team, where 50% of my work consists of mainly supporting observations for the community. We can also be involved in other operations related projects, for example, the development or improvement of operations or instrumentation. In my case, I developed several tools for the VLTI that help during night operations, for instance an automatic fringe search panel for the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER) instrument, and a real-time data display for the VLTI, specifically for interferometric data. The VLTI is probably the most complex part of the observatory as it combines the light coming from four telescopes, passing through tunnels and mirrors, and the light path between all the telescopes needs to be perfectly controlled. I am one of a few astronomers who have the privilege to operate four 8-metre class telescopes simultaneously, which is amazing. With this fellowship, I have improved my technical and scientific knowledge in various fields. I learnt how an observatory works, and I am proud to have been part of the operation and to have participated in the improvement of some VLTI tools.

I am now starting the fourth year of my fellowship. After 240 nights of operating ESO instruments and telescopes, I am not going to Paranal any more as there are no longer any functional duties. I can now focus mostly on my research, whilst also taking time to apply for my next position. I do not know what the future will bring, but I do still love what I am doing, which is probably the most important thing.

Dominika Wylezalek

"Der Mensch muss bei dem Glauben verharren, dass das Unbegreifliche begreiflich sei; er würde sonst nicht forschen."
"One must hold fast by the belief that the incomprehensible is comprehensible; otherwise one would not search."
J. W. v. Goethe

What may sound like a cheesy quote from a different century actually describes quite well why I became an astronomer. I also chose this quote for the first page of my PhD thesis.

When I was five or six years old, on clear starry nights, outside in my parent's garden, I started to wonder how big the Universe was and what was behind its boundaries. Neither my Mum nor my Dad could ever give me a satisfactory answer apart from "it's infinite". When I protested: "No, but it has to have a boundary and there must be something behind it", they would just repeat the same sentence: "It's infinite." That did not satisfy me at all. I think it was then that I decided — although it was not a conscious decision — to learn and study hard enough to become an astronomer and work on understanding the Universe better.

As a teenager, I did not always have this goal in mind. I was easily interested in and excited by many different topics and my "dream job" included everything from being a vet, medical doctor, politician, to restaurant owner. However, I still enjoyed physics the most and decided to start my studies at the University of Heidelberg, which offers a wide range of astronomy classes as part of the physics curriculum.

In my third year in Heidelberg, I started to work at the Landessternwarte Heidelberg (Heidelberg Observatory) for my bachelor thesis project on polarisation measurements of variable active galactic nuclei (AGN). I also got in touch with the extrasolar planet search group there and got the chance to lead observing runs at Lick Observatory, USA. As there is no telescope operator provided at the Coudé Auxiliary Telescope at Lick Observatory, I had to familiarise myself with the telescope, the software, the operation of the dome, the guiding system and even the maintenance of the instrument (for example, refilling liquid nitrogen at the end of the night). In the current era of remote and queue observing, I realise now that my experience at Lick was quite unusual and valuable (especially spending more than a week completely alone at the top of a remote mountain). This experience helped me to develop a deep understanding of what it takes to operate and run a telescope, how much fun it is, and how important it is for an astronomer to understand where and how data are being taken.

Dominika Wylezalek

After finishing my BSc in Heidelberg, I moved to the University of Cambridge in the UK to obtain my master's degree. Although that year was probably the most study-intensive year of my life, I greatly enjoyed having the opportunity to attend lectures by some of the top astronomers in the world and was highly inspired by the academic environment in Cambridge. I vividly remember finding Stephen Hawking's office during one of my first weeks there and taking a selfie with the name plaque.

When I received an offer from ESO for a PhD position in 2011, I did not hesitate to accept it. My thesis project focused on investigating distant galaxy clusters, especially those associated with powerful, radio-loud active galactic nuclei (AGN), and I was supervised by Carlos De Breuck and Joël Vernet. Galaxy clusters are the largest gravitationally bound structures in the Universe and pushing the observations to the highest redshifts, which I did during my PhD, allows us to draw conclusions about the build-up of structure in the Universe over several billion years.

About one year into my PhD, I was given the opportunity to spend six months at the NASA Jet Propulsion Laboratory (JPL) and Caltech working with Daniel Stern, the Principal Investigator of the project. During these six months, I continued working on my primary PhD project but started to become heavily involved in other large collaborations on distant galaxy clusters. I even got the chance to assist the team with observations at the Keck Observatory and Gemini Observatory in Hawaii. Spending two full nights at 4200 m for the Gemini run was certainly quite tough but we were rewarded with great science data and amazing views from the top of the summit in the early morning hours. In my final year as an ESO PhD student, I also joined the *K*-band Multi-Object Spectrograph (KMOS) team for a science verification run to the Paranal Observatory. I tested parts of the reduction pipeline and instrument operation procedure and received training in the commissioning of this unique instrument.

After finishing my PhD degree in 2014, I accepted an offer of a postdoctoral researcher position in Nadia Zakamska's group at the Johns Hopkins University in Baltimore, USA. In Baltimore, I shifted my research focus from studying clusters around powerful AGN to studying the AGN themselves and AGN feedback processes in detail. I am extremely fascinated that the energy output of AGN can impact the evolution of their host galaxies and the build-up of their stellar mass, even though the difference in physical size spans many orders of magnitude. I use multi-wavelength photometric and spectral (preferably spatially resolved, integral field unit [IFU]) observations to address various aspects in the field of AGN feedback studies and galaxy evolution.

The Physics Department of the Johns Hopkins University shares a campus with the NASA Space Telescope Science Institute (STScI) which operates the Hubble Space Telescope, and is heavily involved in the development and management of the James Webb Space Telescope (JWST). The proximity to STScI allowed me to work closely with instrument and telescope scientists and to become familiar with the expected capabilities of the JWST. In late 2016, I put together a team of world experts in my field to write a proposal for Early Release Science observations with the JWST to observe three high redshift quasars with the Mid-InfraRed Instrument (MIRI) and the Near InfraRed Spectrograph (NIRSpec) instruments in IFU mode. The effort was rewarded and the proposal was accepted, making my team one of 13 teams worldwide that will obtain and receive some of the first data taken with the JWST. Although the launch of JWST has been rescheduled twice in the last 12 months, preparing the proposal and the observations and working with the data has been and will certainly be one of the highlights of my career.

In 2017, I moved back to ESO as a Research Fellow where I continue to work on AGN, AGN feedback processes and galaxy evolution. After having worked on this topic mainly with collaborators in the USA and South America, I am now looking forward to growing my scientific network in this field in Europe.

For my functional duties at ESO — which I spend 25% of my time on — I chose to become a member of the Multi Unit Spectroscopic Explorer narrow-field mode (MUSE NFM) commissioning team. Throughout the last year, I have been working very closely with adaptive optics engineers, software developers, instrument scientists, the Instrument and Operations Team, and part of the consortium, including assisting with two commissioning runs at Paranal. I became responsible for various aspects, including: the performance analysis; developing performance models; checking on the fulfilment of the specifications; and working with software developers to implement these models into the exposure time calculator for MUSE. I have been greatly enjoying working and communicating with experts from different professions. This work also allows me to exploit MUSE much better for my own science because I know and understand all its capabilities, limitations and operation modes in much greater detail than before.

With the opening of the ESO Supernova Planetarium & Visitor Centre, the Garching campus has been enriched by an amazing outreach centre that is doing a great job of educating the public about astronomical research and communicating ESO's mission to the public. My own passion for science has been nurtured by local outreach activities, and I enjoy very much "giving back" to society by joining in such events, now not as a participant but as a scientist. I have, for example, given talks during the ESO Open House Day and the European Researchers Night and to high school students in both the USA and Germany. Seeing the sparkle in the eyes of children, teenagers and adults alike when I talk about galaxies and black holes in the Universe is very rewarding, and I hope to inspire some of the younger generation to consider a career in science. In particular, I hope to act as a role model for the next generation of female scientists, who continue to be underrepresented in the fields of physics and astronomy.

I spend most of my free time cooking, travelling, horse riding and hiking in the Bavarian and Austrian Alps. When I am out at night in the middle of the mountains or visit my parents, who also live quite remotely, I am still amazed by the night sky and the vastness of the Universe. Although I understand the many components of the Universe much better today than 25 years ago when I first started to wonder about the size of the Universe, I am more aware than ever before how much we still do not know, and how much is still waiting to be discovered and understood. Contributing my share to this endeavour is what drives me and my research every day.

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Riccardo Giacconi (1931–2018)

Xavier Barcons[1]
Jason Spyromilio[1]

[1] ESO

Opening a new window on the Universe

There are few people who have had such a great influence across all of astronomy as Riccardo Giacconi (b. Genoa 1931, d. San Diego 2018). He studied physics and obtained a PhD in Milan under the renowned cosmic-ray physicist "Beppo" Occhiliani in 1956. Soon after that he moved to the USA, and following stints in Indiana and Princeton, he joined American Science and Engineering (AS&E). Bruno Rossi — another giant in the field — suggested that Riccardo develop an X-ray astronomy programme. At that time the only X-ray source known was the Sun, and judging from the solar X-ray to optical flux ratio, it was clear that the detection of X-rays from other stars would be challenging, to say the least.

A major stride was made in 1962 when one of the AS&E rockets rose above the atmosphere (80 km) for a few minutes, thus setting the scene for Riccardo's 2002 Nobel prize. The payload consisted of three mica X-ray counters[a] that scanned the sky thanks to the spin of the rocket. The objective of that rocket mission was to observe the Moon's albedo in X-rays. However, the telemetry of the two working detectors revealed a very bright X-ray source (Sco X-1 — later identified as an X-ray binary) and a pervasive X-ray radiation dubbed the X-ray background. That date, 12 June 1962, is considered the beginning of X-ray astronomy.

The opening of a new observational window on the Universe provided Riccardo, Herbert Gursky and others at AS&E the momentum they needed to convince NASA to launch the first X-ray observatory into orbit to conduct a census of the X-ray sky. Uhuru (the Swahili word for freedom) was launched from Malindi, Kenya in 1970, and it discovered that accreting black holes — which have much higher X-ray to optical light ratios than the Sun — dominated the X-ray sky.

Riccardo's group moved to Harvard in 1973. From then on he invested a good fraction of his (boundless) energy pushing for imaging X-ray telescopes, his priority being image resolution above any other consideration. That approach resulted in the resounding success of the Einstein Observatory (1978–1983), which demonstrated that the X-ray sky at high galactic latitudes is largely populated by active galactic nuclei which make up most of the cosmic X-ray background that Giaconni had discovered in 1962. His tireless efforts ultimately led to NASA's current X-ray observatory workhorse, Chandra, which was launched in 1999. The Chandra telescope optics deliver sub-arcsecond X-ray imaging, enabling the deepest X-ray surveys to date.

A community of thousands of astronomers have grown up using X-ray observations, following in Riccardo's wake. The field that he initiated, X-ray astronomy, has transformed — starting from two known sources in 1962 (coincidentally the year when ESO was founded) to almost a million X-ray sources that have been catalogued to date. Despite insisting at various science conferences that astronomy should not be qualified with prefixes such as "X-ray" or "optical", it was Riccardo who placed X-rays at the centre of observational astrophysics, for example, by promoting the Chandra Deep Field South project, one of the very first cosmological deep fields studied at all wavelengths.

Moving the Hubble Space Telescope (HST) and ESO's Very Large Telescope (VLT) forward

Riccardo is also remembered for guiding the HST through the near catastrophe that was the spherical aberration in its primary mirror. Assembling teams to solve technical problems, providing the backing for them to operate, and convincing the powers that be that these teams could and would address the problems were skills that Riccardo simply had. Beyond the successful technical and scientific operation of pretty much everything he laid his hands on, Riccardo's vision of how observatories should operate, calibrating the instrument and not just the data, has profoundly changed the way we build and operate facilities. It enabled the construction of data archives that can be reduced and rereduced long after the teams that built the instruments, or the PIs of the programmes that took the data, have moved on.

In 1993, Riccardo left the HST with a recovery plan in place and arrived at ESO at a particularly busy time, whence he embarked upon the changes necessary to deliver the VLT programme. The VLT programme was in full swing, and had been structured according to management techniques appropriate to its size and complexity. Riccardo implemented this transformation across the entire organisation and rapidly aligned the organisational goals with the success of the VLT. He insisted that everything ESO did had science and the astronomical community as the key drivers. He empowered teams to address the challenges and see the job through; he followed their work closely, and was always there to question and challenge, but also to provide support. He contributed the vision and drove ESO to a path of success with tireless enthusiasm and a piercing intellect.

He instituted annual VLT reviews, which later evolved into today's annual overview, and focused ESO staff on the baseline project. He became convinced that ESO needed to evolve and to that end convinced Council both to increase the resources (financial and human) of the organisation and to curtail the programme — pausing the VLT Interferometer (VLTI) — in order to provide the organisation with room to manoeuvre and to successfully complete the VLT. Pausing the VLTI ruffled many feathers but Riccardo ensured the infrastructure was there to resume when the organisation was ready to do so. The famous telescope baseline never lost the ability to do interferometry and, indeed, by the end of Riccardo's tenure the interferometer was back.

The legacy to ESO

Riccardo recognised that the next big project after the VLT and VLTI would require a global effort. The plans in

Europe (ESO/Onsala/Institut de radioastronomie millimétrique [IRAM]/Netherlands Foundation for Research in Astronomy [NFRA]) for a Large Southern Array merged with plans for the MilliMetre Array (MMA) in the USA, to become the Atacama Large Millimeter/submillimeter Array (ALMA). Riccardo launched ALMA from the ESO side, ensuring Europe would become an equal partner with the USA in that programme. After he left ESO in 2000, he became the natural leader for Associated Universities, Inc. (AUI) in the USA, closing the loop on ALMA from the other side of the ocean.

"The immediate purpose of ESO is to provide European astronomers with first-rate observational capabilities of a size and complexity which are not achievable in the national programmes of the member states. In achieving this goal ESO can place European astronomy at a competitive level with respect to astronomical research worldwide. ESO's task has not been accomplished by building the NTT, nor will it be accomplished by building the VLT or the VLTI. It should be understood as an ongoing process in which, from time to time specific facilities or instruments are built, but the overarching role is to support and foster astronomical research in the member states and in Europe.

These simple declarations have a number of obvious consequences which it may, however, be worth stating. The manner in which we conduct the ESO programmes must be directed to maximise scientific returns over the long run. In building new facilities we cannot sacrifice current research which prepares the astronomer who will use them."

So Riccardo began his address to the ESO council in Florence in June 1993, when taking up the duties of Director General (Giacconi, 1993). This enduring vision continues to guide us. Modern-day ESO, with financial discipline, technical excellence, managerial competence and a firm commitment to quality at its core, is very much part of Riccardo's legacy.

References

Giacconi, R. 1993, The Messenger, 72, 1

Notes

[a] The flight spare of that legendary payload can still be seen at the Air & Space Museum in Washington DC, USA.

Personnel Movements

Arrivals (1 October–31 December 2018)

Europe

Belfiore, Francesco (IT)	Fellow
Engelhardt, Max Emanuel (DE)	Product Manager
Hellemeier, Joschua Andrea (DE)	Student
Hughes, Meghan (UK)	Student
Iani, Edoardo (IT)	Student
Kemper, Francisca (NL)	European ALMA Programme Scientist
Kokotanekova, Rosita (BG)	Fellow
Leveratto, Serban (IT)	Mechanical Engineer
Martocchia, Silvia (IT)	Student
Maud, Luke (UK)	ALMA Regional Centre Scientist
Pala, Anna Francesca (IT)	Fellow
Petit dit de la Roche, Dominique (NL)	Student IMPRS
Watkins, Laura (UK)	Fellow
Whitehouse, Lewis James (UK)	Student

Chile

Belmar, Francisco (CL)	Telescope Instruments Operator
Berg, Trystyn (CA)	Fellow
Gendron-Marsolais, Marie-Lou (CA)	Fellow
Hartke, Johanna (DE)	Fellow
Le Gouellec, Valentin (FR)	Student
Mazzucchelli, Chiara (IT)	Fellow
Nuñez, Barbara (CL)	Press Officer in Chile
Roa, Luis (CL)	Mechanical Technician

Departures (1 October–31 December 2018)

Europe

Guillard, Nicolas (FR)	Student
Man, Wing Shan (CN/HK)	Fellow
Peest, Peter Christian (DE)	Student
Scholtz, Jan (CZ)	Student
Arrigoni Battaia, Fabrizio (IT)	Fellow
Barna, Barnabás (HU)	Student
Brunetto, Enzo (IT)	Project Engineer
Löbling, Lisa (DE)	Student
Lu, Hau-Yu (TW)	Fellow
Reiss, Roland (DE)	Electronic Engineer
Tax, Tomáš (CZ)	Student
Tulloch, Simon Mark (UK)	Detector Engineer

Chile

Plunkett, Adele (US)	Fellow
Sanchez, Miguel (ES)	Deputy Program Manager
Sanchez, Joel (MX)	Fellow
Watson, Linda (US)	Fellow

SCHOTT

The ELT secondary mirror blank leaving SCHOTT in Germany. It will undergo final grinding and polishing by Safran Reosc in France.

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

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Front cover: A rare opportunity to see the Moon through the VLT. Following the decommissioning of VIMOS — one of the VLT's longest-serving instruments — ESO engineers and astronomers pointed the telescope at the Moon during twilight and projected its image into a screen. Credit: G. Hüdepohl (atacamaphoto.com)/ESO