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Progress on MUSE
Search for intermediate-mass black holes
The Gaia-ESO public spectroscopic survey
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High-speed Bandwidth between Europe and Paranal: EVALSO Demonstration Activities and Integration into Operations

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A substantial improvement in the connectivity between the Paranal Observatory and ESO Headquarters has been recently made with the completion of the FP7-funded EVALSO project and its integration into the operational information and communications technology of the observatory. Here we describe the demonstration of capabilities, carried out as the final part of the project; some expected applications in the short term; and the possibilities that are opened up by the availability of such high-bandwidth communication links.

Transferring data between Paranal and Garching

The end-to-end operations model of the ESO facilities on Paranal takes place in a geographically distributed environment, with different parts of the lifecycle of observing programmes taking place either in Garching or at the observatory site. Most users of ESO facilities, either directly through the submission and execution of observing programmes, or through the use of archive data, are already familiar with different components of this model, which was initially implemented at the New Technology Telescope (NTT) in 1997, and extended to the Very Large Telescope (VLT) when it began operation in 1999. The model has evolved substantially since then. The latest additions to the Paranal Observatory, the survey telescopes, VISTA and the VST, have been integrated into this model since they began regular operations, and the Atacama Pathfinder Experiment (APEX) and the Atacama Large Millimeter/submillimeter Array (ALMA) science operations also share many of its features.

Operation in such a distributed environment involves the intercontinental transfer of a wide variety of data, most notably (although certainly not only) the large volume of science and calibration data produced by the instruments each night. The data obtained are quickly controlled for quality and used in a sophisticated instrument health-check process, taking place offline in Garching, which ensures that instruments are kept in optimal operating condition at all times. The immediate availability of data through the ESO archive, which is also physically located in Garching, currently enables authenticated users to download their proprietary data as soon as the data are ingested into the archive, typically a few hours or less after acquisition.

The successful implementation of these features requires the availability of sufficient bandwidth for the intercontinental transfer of the data stream. In the first ten years of VLT operations, the combination of bandwidth costs and the fast growth of data production on Paranal required the transfer of data to Garching to take place through physical media (disks), introducing a delay of one to two weeks between the acquisition of the data and their ingestion in the archive. This delay effectively decoupled the day-to-day operation of the observatory from the detailed quality control process taking place in Europe. A major breakthrough took place in 2008 with the implementation of the transfer of the VLT data stream over the internet (Zampieri et al., 2009), which reduced the time lag between acquisition and ingestion into the archive to a few hours at most. Besides allowing end users to access their data much faster, shortening the operations duty cycle also brought significant improvements in the quality control process. However, the available bandwidth was far from allowing remote near-real-time access to Paranal data, and was not sufficient to handle the increase in data production when VISTA, and more recently the VST, began operations, and at the outset their data still needed to be shipped to Garching in disks.

EVALSO demonstration activities

The recently completed EVALSO infrastructure is the definitive step in overcoming these limitations for the current facilities on Paranal, including the survey telescopes and the second generation instrumentation to become available in the near future. EVALSO (for *Enabling Virtual Access to Latin-American Southern Observatories*) is a consortium of nine organisations partly funded by the European Union under its seventh Framework Programme (FP7) with the goal of setting up a high-bandwidth communications infrastructure between Europe and the observatories of Paranal and Cerro Armazones, the latter operated by the Ruhr-Universität Bochum. A description of the project, the overall infrastructure, its technical implementation and the list of participants has been provided in a previous article in *The Messenger* (Filippi, 2010), and further information is available on the web[1].

As part of the FP7 project, EVALSO included a number of Joint Research Activities with the purpose of demonstrating the scientific value of the new infrastructure. One of these activities exploited the capabilities of EVALSO to establish a virtual presence system at the observatory of Cerro Armazones, while the other two tested the data transfer capabilities between Paranal and Europe and the potential of the new link for remotely performing observations from a European institute with sufficient bandwidth.

The VISTA/VIRCAM data stream, averaging approximately 50 GB (compressed) per night, was sent through the EVALSO link for four months, with a measured, sustained Paranal–Garching transfer rate of 9 MB/s. This rate represents a tenfold increase in capacity over that available until now, making possible the transfer of a typical full night of VIRCAM data (the instrument currently dominating the data stream from Paranal) in less than two hours, and demonstrates the feasibility of transferring the entire Paranal data stream, including the VLT, the VLTI (VLT Interferometer), VISTA and the VST, in less than 24 hours (Romaniello et al., 2011). Given the currently available high bandwidth between ESO and the Cambridge Astronomical Survey Unit (CASU) in the UK, where full pipeline processing of all data obtained with VIRCAM is routinely carried out, this will open up the possibility of a significantly faster turnaround time in the processing of VIRCAM data in Cambridge in the future. The flow has been limited until now by the time spent in the intercontinental transfer of the hard disks containing the data.

The test configuration of EVALSO was also intensively used during the commissioning of OmegaCAM, as noted by Kuijken (2011). The use of EVALSO on the commissioning of this instrument clearly illustrated some of the advantages of the new high bandwidth capabilities. It allowed remotely located members of the commissioning team to participate in the analysis of the observations shortly after they were obtained, on nearly the same timescale as the commissioning team working at Paranal, which, given the very high data volumes, would have been impossible without EVALSO. The EVALSO link has also been used in its test configuration to support the backend of the OmegaCAM data flow, making the data obtained with this instrument available for detailed quality control and health checking in Garching on the day following the night when the observations were obtained.

Tests on the feasibility of EVALSO to support VLT observations in remote mode were also successfully carried out in May and June 2011. Most of the tests were conducted from Garching using a Linux laptop equipped with a user installation of the Phase 2 Proposal Preparation (P2PP) tool, as well as standard software for astronomical data analysis, including IRAF and the Skycat tool. One set of tests was carried out by a user located at the Vatican Observatory in Italy, to verify the feasibility from other locations in Europe connected to their corresponding National Research and Education Networks (NREN).

The test observations consisted of the execution on Paranal of Observing Blocks (OBs) prepared by the user while keeping a direct voice channel to exchange information between the user and Paranal Science Operations staff. Both raw and pipeline-processed data reaching a staging area in Garching were retrieved by the user via ftp, and, following a quick analysis of the pipeline-processed data, the OBs were modified and resubmitted for execution. This was intended to reproduce the experience of a future remote user interacting with the observatory mainly through the submission of OBs, and being able to modify them in reaction to the results just obtained in the preceding observation. Thanks to the availability of the EVALSO link the observing efficiency approached that of a visiting astronomer carrying out a similar programme from the control room at the observatory, although the results also highlighted the need for additional tools and upgrades of existing ones, as well as other changes in the VLT operations model, to efficiently enable a possible remote observing mode by regular users of ESO facilities in the future.

Integration of EVALSO into operations

Following the successful verification of the new capabilities offered by the EVALSO infrastructure, ESO proceeded towards integrating it into the operations network of the observatory, which was completed in mid-December 2011 and is expected to become fully functional in mid-February 2012. The link from Santiago to Garching is now handled by dual VPN tunnels, one over a link supplied by a commercial provider, and the other by REUNA/RedClara, the Chilean NREN that is one of the EVALSO partners (see Figure 1 of Filippi [2010] for more detail). The passing of traffic over the links is configured using policy-based routing and access control lists to determine the path to be taken for each traffic type, with scientific data regularly taking the REUNA/RedClara link. The same configuration is applied at Paranal, with the EVALSO link being used for the transfer of EVALSO data.

The functionality of the EVALSO/REUNA link has also been verified by the transfer to Garching of scientific data obtained from La Silla, which has worked flawlessly since mid-January 2012. The Paranal transfer through the EVALSO link will start operating regularly in mid-February 2012, with the whole of the VLT/VLTI data stream and all the VST calibration frames being routed through it. VISTA and the rest of the VST data stream will be added shortly after, following some optimisation to be done on the science data transfer software (Zampieri et al., 2009).

The data transfer capabilities offered by EVALSO are already sufficient to significantly improve end-to-end operations by ensuring that the current backend operations procedures applied to the VLT/VLTI data stream thus far can be extended to the entire data stream from all the facilities on Paranal, including the full set of VLT and VLTI second generation instruments as they become operational. The performance is expected to further improve through the optimisation of the data transfer software and the expanded capabilities of the transoceanic link provided by the upgrades of ALICE2. This research infrastructure was created with EU support in 2003 for the establishment of high-capacity interconnectivity within South America and transatlantic connection to European National Research Networks. The high bandwidth connectivity with the observatory provided by EVALSO will in this way open new possibilities, such as a virtual presence at the observatory and a possible implementation of additional observing modes in future VLT operations.

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Links

[1] EVALSO web page: http://www.evalso.eu

News of the MUSE

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We report on progress of the Multi Unit Spectroscopic Explorer (MUSE), a second generation VLT panoramic integral field spectrograph. MUSE is now in its final phase of integration, testing and validation in Europe. The instrument is described and some results of its measured performance are shown.

The Multi Unit Spectroscopic Explorer (MUSE) is a second generation Very Large Telescope (VLT) panoramic integral field spectrograph. MUSE has a field of 1 × 1 arcminutes, sampled at 0.2 × 0.2 arcseconds and is assisted by the VLT ground layer adaptive optics facility using four laser guide stars (Arsenault et al., 2010). The simultaneous spectral range is 0.465–0.93 μm, at a spectral resolution of ~ 3000. MUSE couples the discovery potential of a large imaging device to the measuring capabilities of a high-quality spectrograph, while taking advantage of the increased spatial resolution provided by adaptive optics. MUSE also has a high spatial resolution mode with a 7.5 × 7.5 arcsecond field of view sampled at 25 milliarcseconds. In this mode MUSE should be able to obtain diffraction-limited datacubes in the 0.6–0.93 μm wavelength range.

MUSE has been presented in Bacon et al. (2006). At that time the project was in an early stage (preliminary design phase). Meanwhile the concept has transformed into an impressive piece of hardware. MUSE is now entering its very final phase of integration, testing and validation in Europe.

The MUSE hardware is composed of 24 identical modules, each consisting of an advanced slicer, a spectrograph and a 4k × 4k pixel detector. A series of fore-optics and splitting and relay optics derotates and partitions the square field of view into 24 sub-fields. These optics systems will be placed on the Nasmyth platform between the VLT Nasmyth focal plane and the 24 integral field unit (IFU) modules.

Instrument innovations

Among the numerous technical innovations utilised in the instrument it is worth mentioning a few important achievements.

The slicer, a key element of the project, is a compact stack of spherical off-axis two-mirror systems. Each slicer incorporates an array of 48 thin slices, which are assembled with a very high precision, and kept in place by optical contacting. This array faces another array of 48 small off-axis spherical pupil mirrors. The system rearranges the input image geometrically into 48 small pseudo-slits with only two optical reflections. This guarantees the highest possible throughput. The production of the 24 slicers, i.e., 2304 high precision optical elements, has been contracted to Winlight Optics. In January 2012, they delivered 23 slicers and the remaining one is expected very soon. It took a significant time to fine tune the industrial production and alignment pro-

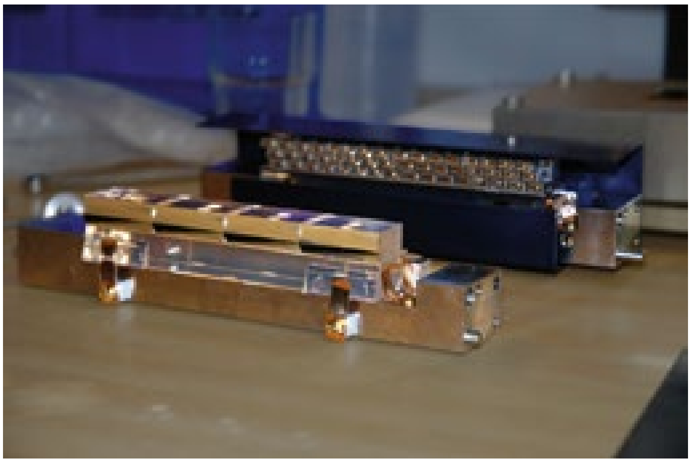

Figure 1. One of MUSE's slicer image dissectors and the focusing mirror arrays are shown before assembly in the laboratory.

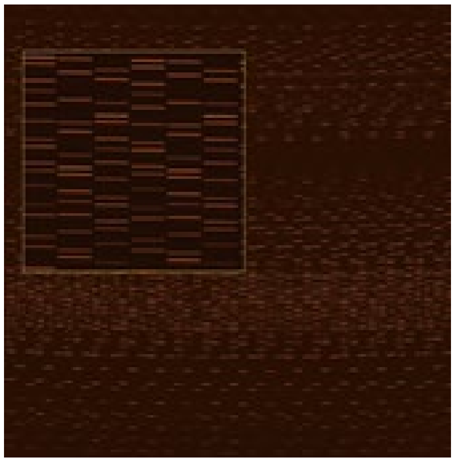

Figure 2. IFU technical first light image. This image shows the first exposure of a complete IFU obtained in the laboratory. This picture was obtained by exposing the IFU to a set of neon, xenon and mercury–cadmium arc lamps for a few seconds. Part of the image is zoomed to display the arc lamp emission lines produced by six slices in more detail.

cesses, but today all the slicers we have in hand achieve very high performance. Figure 1 shows one of the assembled slicers.

Each slicer is located at the entrance of a spectrograph. The 24 spectrographs have a compact design and incorporate a wide spectral range volume phase holographic (VPH) grating specifically designed for MUSE by Kaiser Optical Systems. Winlight is also in charge of spectrograph production, and has delivered 19 units so far. After alignment, the slicer is attached to the front part of the spectrograph, while the detector vessel connects to the rear side. This assembly constitutes one integral field unit. The system is then aligned and qualified. The performance of each IFU is carefully checked and monitored. The IFU point spread function is a major contributor to the overall image quality budget and determines the final spectral performance. We are pleased to report that the IFUs achieve a very high and homogeneous image quality, even better than the original specifications, which were already considered as tight. Figure 2 shows the first image of an exposure of an arc lamp.

Each detector vessel incorporates one 4k × 4k 15 μm deep depletion CCD device with improved quantum efficiency in the red wavelength range. The company e2v delivered 26 top quality detectors to ESO. These detectors implement an innovative graded index anti-reflection coating, which is optimised according to the wavelength of light hitting each pixel of the detector. This gives a significant boost to the quantum efficiency and reduces the fringing. All the CCDs have been mounted in their detector heads, and have been characterised by the optical detector team at ESO, and found to be within specification. As proper align-

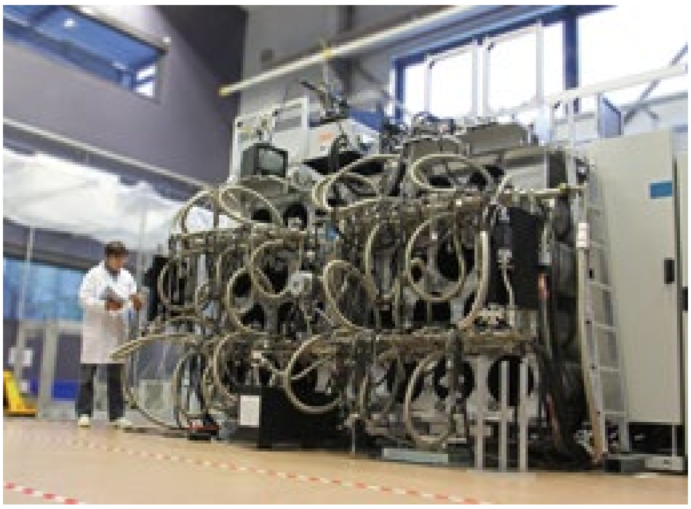

Figure 3. Rear view of MUSE in the CRAL integration hall, showing the large cryogenic system in charge of cooling and vacuum control for the 24 cryostats. The large IFU holes in the main structure are visible between the cooling cables.

Figure 4. Front view of MUSE in the CRAL integration hall. The two electronics cabinets (one for the cooling system, the other for the fore-optics and calibration unit mechanism and lamps) can be seen in the foreground. The front part of the fore-optics is visible at the top of the main structure. It faces an optical system which simulates the VLT light beam.

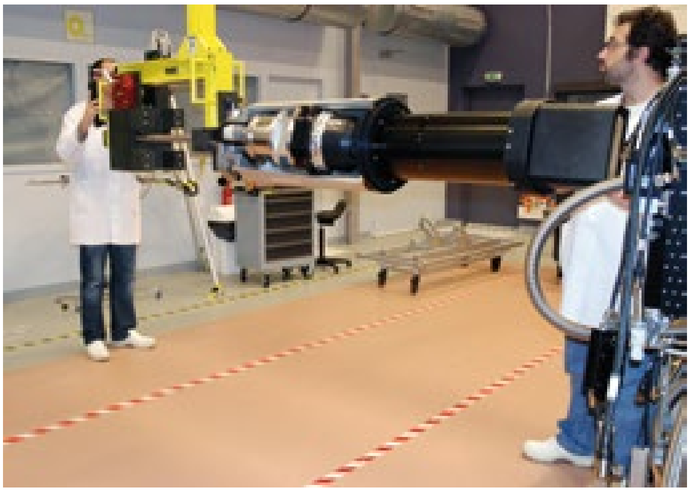

Figure 5. First IFU insertion. One complete IFU is visible before its insertion into the main structure. A dedicated tool (in yellow) has been built to ease the insertion while minimising the risk of damaging the delicate image slicer, located in the front of the IFU, or the cables of the cooling system.

Figure 6. The fore-optics system attached to the integration hall crane can be seen before its descent onto the main structure.

ment of the detector with respect to the spectrograph is critical, the 24 completed detector heads have been systematically checked at AIP in Potsdam using a single reference spectrograph.

To improve further the total efficiency of the instrument, we have replaced the protected enhanced silver coating originally envisioned for the seven mirrors of the optical train by a dedicated 80-layer dielectric coating from Balzers Optics. The solution was extensively tested for durability under severe constraints: humidity, temperature change and scratch. The stress induced by the optical coatings on the substrates was also checked and found to be tolerable.

Integration at CRAL

Early in 2011, ESO finalised the construction of the impressive vacuum and cryogenic system, based on liquid N_2 continuous flow cryostats, and its control electronics, and delivered it to CRAL in Lyon. It was followed a few months later by the equally impressive MUSE main structure from IAG, the fore-optics subsystem from IRAP, and the calibration unit from AIP. Figure 3 shows a rear view of the main structure and Figure 4 a view from the front. The pieces were put together and a first IFU inserted (see Figures 5 and 6). A first set of mirrors and lenses of the splitting and relay optics has been aligned such that we obtained first light in late December, involving a full optical path, from the calibration unit to the detector plane. Fine alignment is in progress, but we can already confirm the excellent image quality of the system; a wonderful Christmas gift.

In parallel to the visible hardware assembly, a lot of effort has gone into the control and data reduction software. Full-scale tests with simulated astrophysical scenes have started and demonstrate that the system is able to handle the huge data volume provided by the instrument.

We are now proceeding to align and assess the performance of the 24 channels, in parallel with the alignment of the remaining IFUs. The global tests and performance verification will be concluded by the preliminary acceptance review in Europe (PAE), which is expected in October this year. The instrument will then be sent to Paranal for the re-integration and commissioning phase. This period is expected to take a significant fraction of 2013.

Prospects

With its 400 megapixels per frame and 90 000 spectra in one exposure, MUSE is already the largest integral field spectrograph ever built. The performance measured in the laboratory demonstrates that it should also meet its very ambitious specifications on the telescope. In some critical areas such as image quality and throughput it is even better than the original specifications. Once installed at the Nasmyth focus of the VLT's Unit Telescope 4, MUSE will immediately provide the ESO community with a unique and powerful tool to address key scientific questions in a large number of astrophysical fields. A year later MUSE will be coupled to the Adaptive Optics Facility (Arsenault et al., 2010) using the GALACSI adaptive optics module. The expected spectacular gain achieved in spatial resolution without any loss in throughput and with almost full sky coverage will boost the MUSE performance by another substantial factor.

References

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Links

MUSE public website: http://muse.univ-lyon1.fr

APEX–SZ: The Atacama Pathfinder EXperiment Sunyaev–Zel'dovich Instrument

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The APEX–SZ instrument was a millimetre-wave (150 GHz) cryogenic receiver for the APEX telescope designed to observe galaxy clusters via the Sunyaev–Zel'dovich Effect (SZE). The receiver contained a focal plane of 280 superconducting transition-edge sensor bolometers equipped with a frequency-domain-multiplexed readout system, and it played a key role in the introduction of these new, robust, and scalable technologies. With 1-arcminute resolution, the instrument had a higher instantaneous sensitivity and covered a larger field of view (22 arcminutes) than earlier generations of SZE instruments. During its period of operation from 2007 to 2010, APEX–SZ was used to image over 40 clusters and map fields overlapping with external datasets. This paper briefly describes the instrument and data reduction procedure and presents a cluster image gallery, as well as results for the Bullet cluster, Abell 2204, Abell 2163, and a power spectrum analysis in the XMM-LSS field.

Galaxy clusters

Galaxy clusters comprise dark matter and constituent galaxies with hot, low density ionised gas filling the space between the galaxies. This gas, known as the intracluster medium (ICM), dominates the baryonic mass in clusters. Thus, galaxy clusters are important laboratories for studying various astrophysical phenomena in great detail, for example, cluster formation and dynamics, cluster mergers and their associated shock waves (which are sites of cosmic ray acceleration), the cosmic ratio of dark matter to baryonic matter density, active galactic nuclei feedback, the evolution of galaxies in the ICM, heat transport processes, and plasma instabilities (Sarazin, 1988).

In addition, galaxy clusters offer a unique probe into the composition and evolution of the Universe. They are the most massive gravitationally-collapsed objects and directly map large-scale structure over a large range of redshifts. Consequently, measuring the evolution of the cluster number density places powerful constraints on the parameters that govern the growth of structure. These parameters are, notably, the mass energy density and dark energy density of the Universe, the dark energy equation of state, and the matter power spectrum normalisation (Carlstrom et al., 2002).

The hot ICM is observable at millimetre-wavelengths via the SZE (Sunyaev & Zel'dovich, 1970). In the SZE, about 1 % of cosmic microwave background (CMB) photons incident on the cluster are scattered by free intracluster electrons. The resulting signal distorts the CMB blackbody spectrum and is visible as a temperature decrement (increment) at frequencies below (above) 217 GHz. The SZE surface brightness is proportional to the integrated gas pressure along the line of sight through the cluster. Since the SZE is a scattering effect seen relative to the CMB, and the scattered and unscattered photons are redshifted together, the SZE signal is independent of the redshift of the scattering cluster. In contrast, X-ray and optical surface brightness dim with increasing redshift. The redshift independence makes the SZE a uniquely sensitive method for discovering and observing distant clusters.

Instrument overview

APEX–SZ observations were performed at 150 GHz (2 mm) from the 12-metre APEX telescope (Güsten et al., 2006). Technical details of the receiver can be found in Schwan et al. (2011). The telescope was

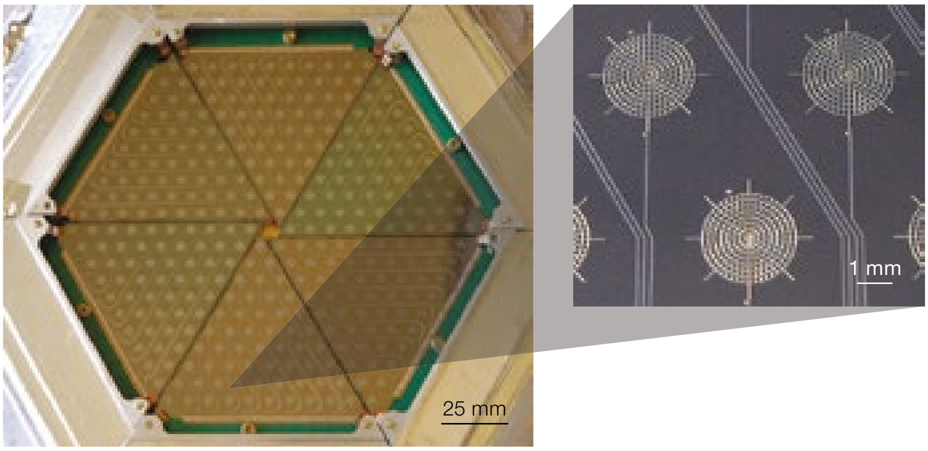

Figure 1. The TES bolometer array, with inset showing three spiderweb bolometers. Six identical triangular sub-arrays are assembled into a single planar array, 133 mm in diameter, containing 330 bolometers. Each bolometer has two leads which run from the spiderweb to bonding pads at the edge of its triangle, visible as light traces between the bolometers.

commissioned by the Max-Planck-Institut für Radioastronomie, ESO and the Swedish Onsala Space Observatory for use with bolometric and heterodyne receivers. It is located near the ALMA site at an altitude of 5107 metres on Llano de Chajnantor in the Atacama desert in Chile, which has exceptionally low water vapour conditions. In addition, the low latitude of the site (23 degrees south) allows targeted observation of clusters with rich multi-frequency datasets. Overlapping observations at different wavelengths enable a more complete study and characterisation of clusters.

The telescope beam was coupled to the APEX receiver by a series of reimaging optics inside the Cassegrain cabin. The full optical system had 58-arcsecond FWHM (Full Width at Half Maximum) beams, diffraction-limited performance, over a 22-arcminute field of view (FoV). This large FoV enabled APEX–SZ to map the large angular size of low redshift clusters, where the SZE signal can extend beyond a 10-arcminute radius.

Within the receiver, the APEX–SZ focal plane was 133 mm across and consisted of 330 feedhorn-coupled TES (transition-edge sensor) bolometers. Of these, 280 detectors were read out. The detectors and readout system are described in the next section. The horn array was machined from a single aluminium block and mounted above the planar focal surface. Each bolometer was centred behind a cylindrical waveguide in the horn array. There was a small gap between the horn array and the bolometers to provide thermal isolation. Radiation not absorbed by a detector could leak radially to neighbouring detectors or be reflected back through the horns. This leakage resulted in a small, ~ 1 %, optical cross-talk between adjacent bolometers.

The TES bolometers and frequency-domain multiplexed (fMUX) readout system used in the APEX–SZ focal plane have low noise, but require a cryogenic system for their operation. The receiver interior was cooled by a closed cycle pulse-tube cooler with cold stages at 60 K and 4 K. The mechanical cooler eliminated the need for open reservoirs of liquid cryogens, greatly simplifying the design and construction of the cryostat while reducing the cost and difficulty of remote observations. The bolometers were further cooled to 280 mK by a three-stage helium sorption fridge.

Detectors and readout

Each APEX–SZ bolometer consists of an optical absorber coupled to a TES that is connected to a thermal reservoir by a weak thermal link. The absorbing element is a 3 mm diameter gold spiderweb (Figure 1). The spiderweb shape absorbs millimetre-wave radiation, provides a small cross-section to cosmic rays and minimises the heat capacity of the absorber. Changes in optical power incident on the absorber are measured by the TES mounted at its centre. The TES is a thin superconducting film with a transition temperature higher than the reservoir temperature. A constant bias voltage is applied across the TES so that the total applied power (the electrical power dissipated in the TES plus optical power incident on the absorber) raises the temperature of the sensor to precisely the transition temperature. An increase (decrease) in the incident optical power produces a cancelling decrease (increase) in electrical power. Since the voltage bias is held constant, the change in electrical power is measured as a change in current through the sensor.

The bolometers are fabricated using standard photolithographic techniques. The absorber, the TES and the leads to bias the TES are deposited onto a 1 μm thick, low-stress silicon nitride (LSN) spiderweb membrane. The LSN spiderweb is suspended by eight LSN legs above a ~ 20 μm vacuum gap etched in the silicon. The gap thermally isolates the absorber from the silicon substrate. The thermal conductance of the bolometer is set by a gold thermal link that runs from the TES to the thermal reservoir, parallel to the bias leads. The APEX–SZ detector array is assembled from six identical 55-element, triangular subarrays (Figure 1).

The APEX–SZ TES bolometers are read out with a SQUID (Superconducting Quantum Interference Device) amplifier fMUX, which allows several detectors to be read out by a single 4 K SQUID amplifier connected through a single pair of wires (Lanting et al., 2004). Readout multiplexing enables the use of large detector arrays by greatly reducing the thermal load on the low temperature stage, the complexity of cold wiring and the system cost. The APEX–SZ system uses seven detectors read out by one SQUID amplifier in each multiplexer module.

In the fMUX system, the bolometers are biased with alternating voltages at carrier frequencies (0.3–1 MHz) that are much higher than the bolometer thermal bandwidth, so the bias deposits a constant power on the sensor. Each bolometer in the module is biased at a different frequency. As described above, changes in incident radiation modulate the current through the bolometer. This amplitude modulation translates the absorbed signal spectrum to sidebands centred around the carrier bias frequency. Since the currents from the different bolometers are separated in frequency, they can be combined and transmitted to the SQUID amplifier with a single wire. Furthermore, the bolometers are connected through series inductor–capacitor circuits, each of which is tuned to the appropriate bias frequency, so all bias carriers can also be fed through a single line. As a result, each multiplexer module requires only a single pair of wires from the low temperature stage to the 4 K stage to read out all the bolometers in the module.

Imaging techniques

With bolometer receivers operating near the performance limit set by statistical photon noise, the main challenge in long-integration, millimetre-wave observations of spatially extended signals is the contamination from atmospheric noise. The emission from the turbulent atmosphere carrying water vapour typically exhibits a Kolmogorov power spectrum (Tatarskii, 1961), with power increasing steeply with increasing angular scale. It also varies with time relative to the celestial signal. The APEX–SZ observation pattern and data reduction techniques exploit these characteristics to mitigate atmospheric noise.

APEX–SZ used a circular drift scan pattern to observe clusters. In the circular drift scan, the telescope performs circular scans which are stationary in azimuth and elevation. After the source drifts across the array FoV, the telescope slews to the new source position. This circular drift scan pattern combines constant low amplitude acceleration for efficiency with modulation of celestial signals at timescales faster than typical atmospheric variations.

The data reduction algorithms remove the low frequency, large-scale atmospheric noise using high-pass filters in the time and spatial domains. A low-order polynomial is fitted and subtracted from the data timestream for each channel. Additionally, a low-order two-dimensional spatial polynomial is fitted across the array for each time step. Figure 2 shows 28 cluster images measured with this procedure.

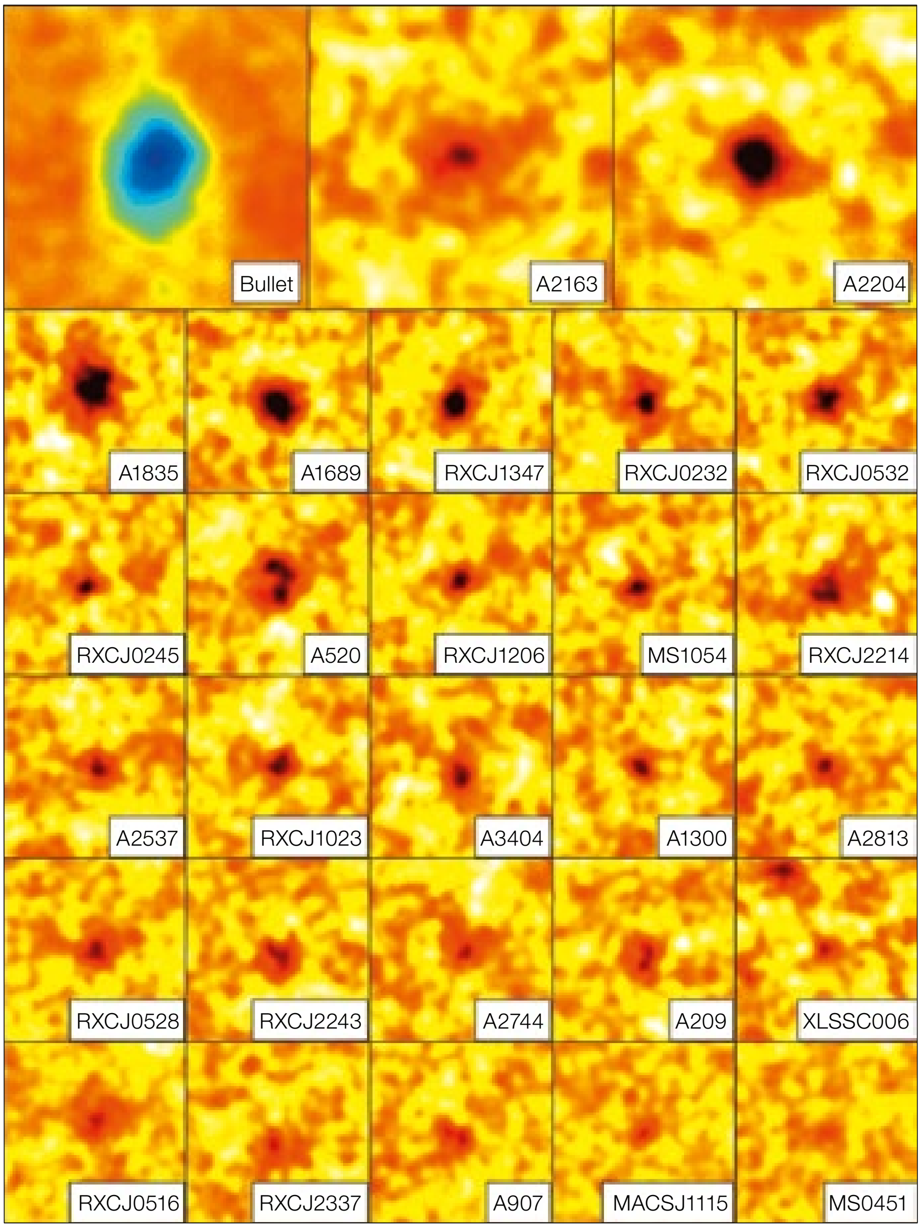

Figure 2. Signal-to-noise (S/N) maps of 28 clusters in which the cluster signal map is divided by a noise estimate derived from jack-knife maps (a weighted average of all scan maps in which a randomly selected half of the scan maps are multiplied by –1). The signal and noise maps are smoothed by convolving with a 1-arcminute FWHM Gaussian function. Each image is 15 arcminutes square. The Bullet map has a peak S/N roughly four times that of any other cluster and is shown with a different colour table; all other clusters have the same S/N scale.

The procedure for removing atmospheric noise also removes cluster signal, and the effect is especially pronounced for clusters of large angular size. We use a point source transfer function (PSTF) to measure the effect of the instrument beam and data filtering on the resulting cluster map. Since the filtering process is linear, the PSTF accurately encodes the distortion of the cluster signal. To generate the PSTF, simulated point sources are inserted into the real timestream and their spatial distortion is measured post-processing. The transfer function encodes information about the imaging quality. In

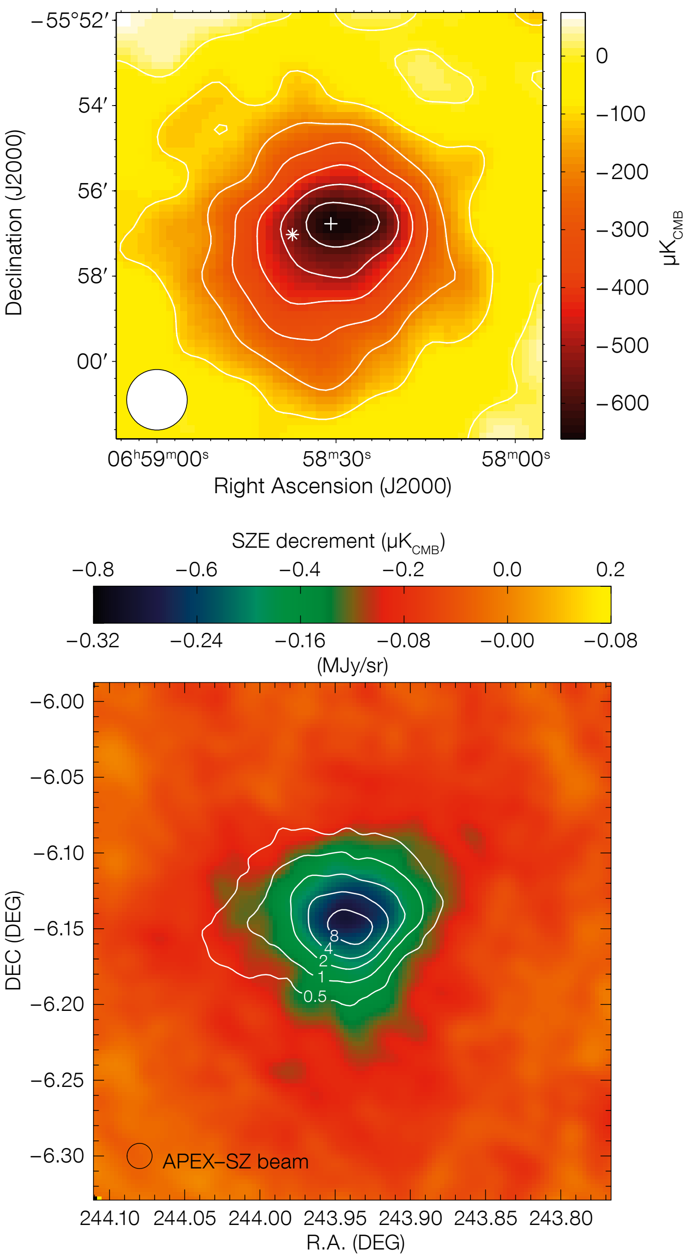

Figure 3. APEX–SZ maps of two clusters. Top: Map of the Bullet cluster (from Halverson et al., 2009). The circle in the lower left corner represents the 85-arcsecond FWHM map resolution, which is the result of the instrument beam, data reduction filter, and 1-arcminute FWHM Gaussian smoothing applied to the map. The contour intervals are 100 μK_{CMB}. The + marker indicates the centroid position of the best-fit elliptical β-model. The * marker indicates the position of a bright, dust-obscured, lensed galaxy, which is detected at higher frequencies (e.g., at 350 GHz by LABOCA; Johansson et al., 2010), but does not significantly contaminate the measurement at 150 GHz. Bottom: Map of Abell 2163 (from Nord et al., 2009). The APEX–SZ map, deconvolved from the effects of the transfer function, is overlaid with XMM-Newton X-ray contours in units of 10^{-13} erg s^{-1} cm^{-2} $arcmin^{-2}$.

particular, negative sidelobes indicate missing spatial information on larger angular scales. This is very similar to an interferometric synthesised beam, where the inner portion of the Fourier plane, corresponding to very short baselines, is often not sampled. In both cases, the observation process is designed so that the most relevant information is most densely sampled.

Figure 3 shows maps of the Bullet cluster and Abell 2163 made using two different schemes to mitigate the effect of noise filtering on the sky signal. The Bullet cluster is a system of two merging clusters (mass ratio ~ 1:10), which shows an offset between the gas and dark matter (Clowe et al., 2006; also Figure 5). The map of Figure 3 is produced by masking a circular region centred on the cluster source prior to fitting for the low-order polynomial filters, then applying the filters to the entire dataset. The masking procedure limits attenuation of the cluster extended emission at the expense of increased map noise. The observations and data processing are detailed by Halverson et al. (2009). The cluster map of Abell 2163 is produced by applying a procedure similar to the *CLEAN* algorithm used in radio interferometry to deconvolve the signal image and PSTF. The procedure, detailed by Nord et al. (2009), allowed the first direct reconstruction of the density and temperature profiles in a cluster without a parametric model.

Cluster gas constraints from the SZE and X-ray

Joint SZE and X-ray observations allow strong constraints to be placed on the cluster gas. The surface brightness of the SZE signal is proportional to the electron density and the temperature of the intracluster gas. X-ray emission from the gas is dominated by thermal *bremsstrahlung*, which is roughly proportional to the square of the density and the X-ray cooling function, itself a weak function of temperature. Multi-frequency data enable detailed measurements of the cluster gas, including determination of the gas temperature and mass, as well as their distributions.

Halverson et al. (2009) fit the intracluster gas of the Bullet cluster to an elliptical isothermal β-profile (Cavaliere & Fusco-Femiano, 1978) convolved with the PSTF. A Markov-chain Monte Carlo approach is used to find the maximum likelihood in parameter space with an X-ray-derived prior on β. The analysis yields a core radius r_c = 142 +/− 18 arcseconds, an axial ratio 0.889 +/− 0.072, and a central temperature decrement −771 +/− 71 μK_{CMB} (in units of temperature referred to a source at the CMB temperature), including a +/− 5.5 % flux calibration uncertainty. With a map of projected electron density from Chandra data, the SZE-derived gas (electron) temperature is T_e = 10.8 +/− 0.9 keV. This temperature is lower than some previously reported X-ray temperatures, which could be biased towards hot, compact regions. On the other hand, the gas mass fraction derived from the SZE map (under the approximation of hydrostatic equilibrium), is in good agreement with estimates from X-rays.

Nord et al. (2009) and Basu et al. (2010) further explore cluster physics with SZE data combined with X-rays. Nord et al.

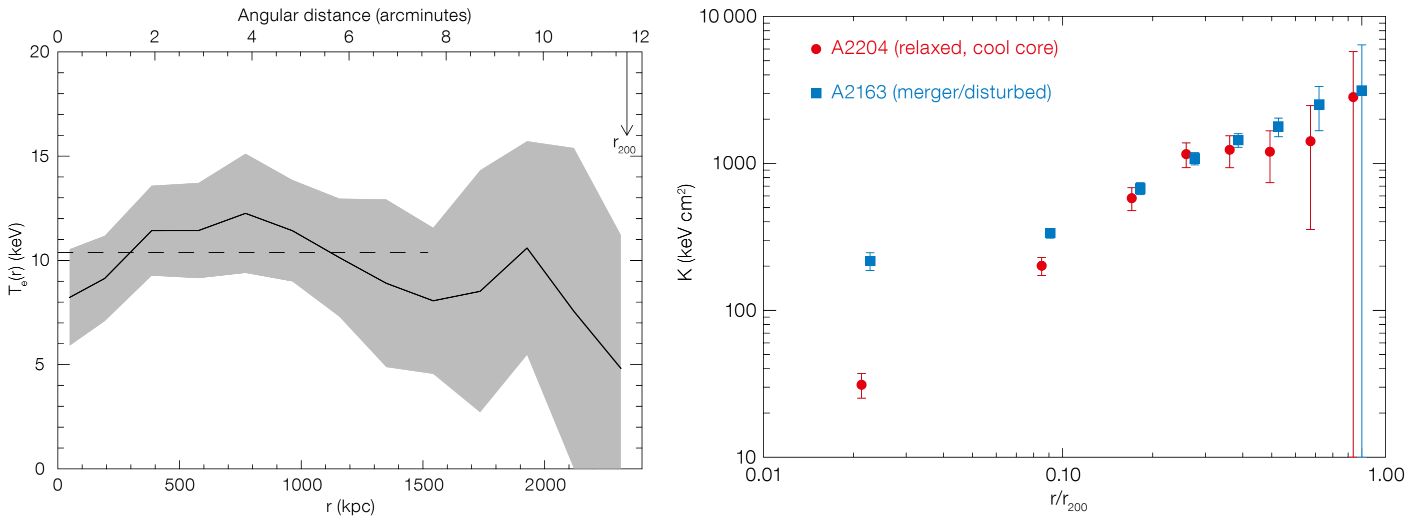

Figure 4. Derived radial profiles of cluster gas properties. Left: De-projected temperature for Abell 2163 with 1σ uncertainties (from Nord et al., 2009). The vertical arrow labelled "r_{200}" marks the aproproximate virial radius (i.e., outer boundary) of the cluster. Right: Entropy derived from APEX–SZ and X-ray data for the relaxed cluster Abell 2204 (red circles) and the merging cluster Abell 2163 (blue squares).

(2009) derive gas density and temperature profiles for Abell 2163 via the Abel integral in Silk & White (1978). The derived temperature profile shown in Figure 4, representative of the bulk of the gas, is in excellent agreement with the high gas-temperature estimates from X-ray data. The profiles have been converted to yield non-parametric estimates for the total mass and the gas mass, giving a gas mass fraction profile, which again is consistent with X-ray analyses. Nord et al. (2009) also combine the APEX–SZ SZE measurements of Abell 2163 at 150 GHz with 345 GHz measurements from the LABOCA camera on APEX and published measurements at other frequencies to place constraints on the peculiar velocity of the cluster. Basu et al. (2010) present an analysis of the relaxed cluster Abell 2204, where the assumption of spherical symmetry should be especially valid. A comparison of the derived entropy profiles (entropy is $T_e\, n^{-2/3}$, where T_e and n are the electron temperature and density, respectively) for Abell 2204 and Abell 2163 shows that the entropy in the centre of a relaxed cluster is much lower than in a violently disturbed merging cluster and follows a power law (Figure 4). This result

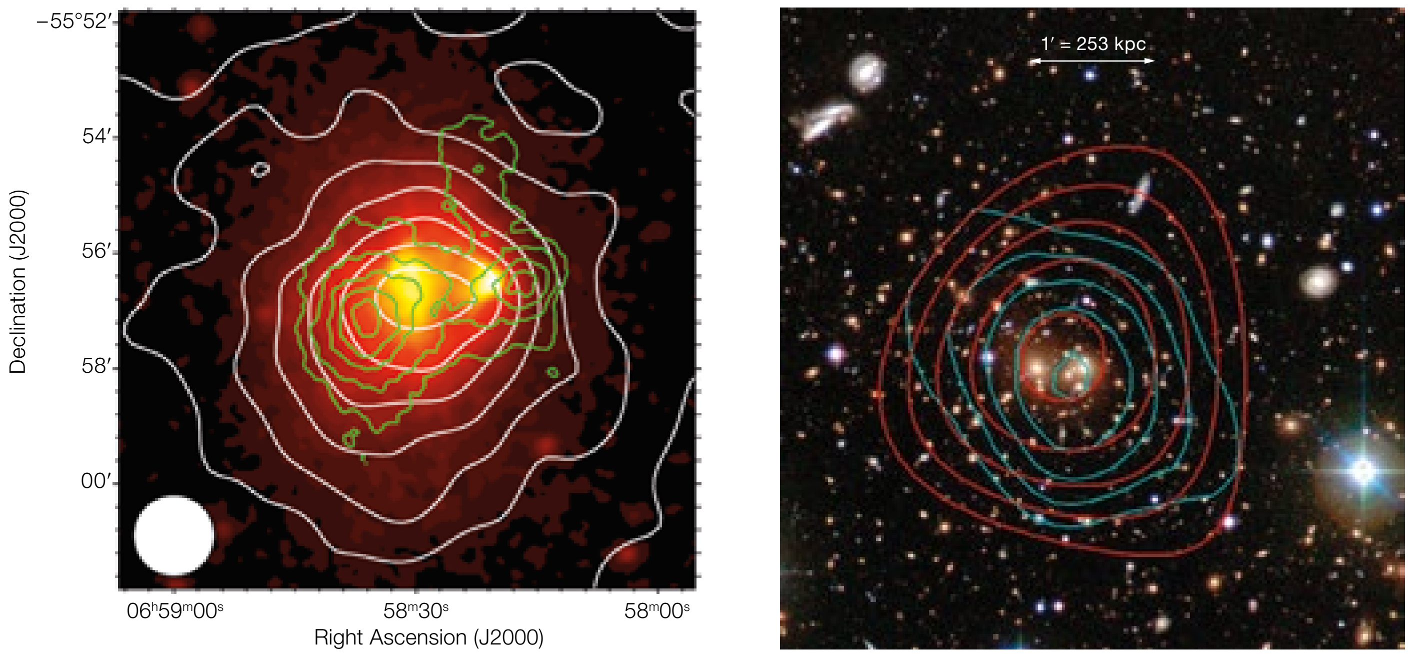

Figure 5. Left: Multi-wavelength overlay (from Halverson et al., 2009) on the Bullet cluster X-ray (XMM-Newton) colour image with SZE contours in white (100 μK_{CMB} level intervals) and the weak-lensing surface mass density reconstruction contours in green. Right: *B, V, R* colour image of the central region of RXCJ0232.2-4420 (z = 0.28) with SZE contours in cyan (–90, –110, –130, –150, –170 μK_{CMB}) and smoothed weak-lensing convergence contours in red (0.10, 0.11, 0.12, 0.13, 0.14).

agrees with previous X-ray studies, but is derived independently without X-ray spectroscopy.

Power spectrum analysis

Reichardt et al. (2009) use an SZE image taken with APEX–SZ within the XMM-LSS field (0.8 square degrees, centred on the medium mass cluster XLSSUJ022145.2-034614, with 12 μK_{CMB} root mean square noise at the centre) for statistical analysis of the temperature fluctuations from undetected clusters and other sources. This type of fluctuation analysis applied to large datasets places strong constraints on σ_8, the normalisation of the matter density power spectrum on the scale of roughly 10 Mpc. The power spectrum of the integrated SZE from all clusters along the line of sight scales as σ_8^7. The APEX–SZ image was the most sensitive fluctuation measurement at 150 GHz at the time, with the resulting constraint on the matter fluctuation amplitude being $\sigma_8 < 1.18$ at 95 % confidence. Determination of the constraint requires consideration of contamination of the SZE signal by other populations, such as radio sources or dusty submillimetre (sub-mm) galaxies, which can be correlated with clusters as members or via gravitational lensing. The Reichardt et al. (2009) analysis estimates the contribution of sub-mm galaxies to the power spectrum at 150 GHz to be $C_\ell = 1.1^{+0.9}_{-0.8} \times 10^{-5}$ μK^2 (the amplitude of the angular power spectrum for spherical harmonic multipole index ℓ in the range 3000–10 000 assuming flat band powers) or $1.7^{+1.4}_{-1.3}$ Jy^2 sr^{-1}. Assuming that the same sources are responsible for the power fluctuations measured by BLAST at 600 GHz, the spectral index of the source population is $2.6^{+0.4}_{-0.2}$. The Atacama Large Millimeter/submillimeter Array (ALMA) will resolve remaining questions about contaminating sources by providing the missing statistical information on population counts over all relevant wavelengths and by providing the ability to directly correct SZE images for their point source contamination.

Future directions

APEX–SZ was a pioneering instrument for arcminute resolution SZE cluster observations, advancing bolometer and readout technology and applying multi-wavelength data analysis to constrain cluster gas physics. The TES bolometer array with fMUX readout has been adopted for dedicated instruments with larger arrays, notably the South Pole Telescope, with 960 detectors, and POLARBEAR (Arnold et al., 2010), a Berkeley CMB polarisation experiment, with over 1200 detectors.

APEX–SZ took over 800 hours of scientific data during its four years of operations, targeting over 40 X-ray selected clusters in a wide range of mass and redshift. Over 30 of these clusters were detected with high significance. The analysis of the full dataset is still ongoing (Bender et al., 2012). These observations are being used to study the scaling of the SZE signal with cluster mass (hydrodynamical and weak lensing).

A major aspect of the recent and future work is a multi-wavelength analysis of clusters imaged with APEX–SZ (Figure 5). For this reason, an optical follow-up programme has been conducted using the Wide Field Imager (WFI) at the 2.2-metre MPG/ESO telescope. Deep *B*-, *V*- and *R*-band images obtained during 42 nights, together with archival data from WFI and Subaru Suprime-Cam, provide excellent weak-lensing data for 35 galaxy clusters at redshift 0.15–1 for the study of SZE and weak-lensing scaling relations. Our multi-frequency cluster data provide a unique sample to study cluster mass scaling laws and baryon physics in unprecedented detail.

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NASA, ESA, ESO, CXC & D. Coe (STScI)/J. Merten (Heidelberg/Bologna)

Composite image of the complex galaxy cluster merger Abell 2744 (redshift 0.308) formed by combining visible light images from NASA/ESA Hubble Space Telescope and VLT with an image of the hot intracluster gas (pink) from NASA Chandra X-ray Observatory data. A reconstruction of the dark matter in the cluster is overlaid (blue). See Science Release eso1120 for full details.

ESO/APEX/T. Preibisch et al. (Submillimetre); N. Smith, University of Minnesota/NOAO/AURA/NSF (Optical)

The cool dust in the Great Nebula in Carina (NGC 3372), situated at a distance of 2.3 kiloparsecs, is highlighted (orange) in this combination of APEX Large Apex BOlometer Camera (LABOCA) and optical observations. The LABOCA images were made at a wavelength of 870 μm sensitive to emission from dust at around 30 K. The optical image was made by the Curtis Schmidt telescope at the Cerro Tololo Interamerican Observatory. Further information can be found in Release eso1145.

Determining the Cepheid Period–Luminosity Relation Using Distances to Individual Cepheids from the Near-infrared Surface Brightness Method

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The near-infrared surface brightness method has been applied to 111 Cepheids in the Milky Way, the Large Magellanic Cloud and the Small Magellanic Cloud, and distances and luminosities to the individual stars have thus been determined. As the Cepheid populations in these galaxies have significantly different metallicities, the effect of metallicity on the Cepheid Period–Luminosity (PL) relation can be directly determined. We show that the *K*-band PL relation is very insensitive to abundance and argue that it is the best Cepheid PL relation for distance determination.

Motivation

The Cepheid Period–Luminosity relation provides a crucial step on the distance ladder in the quest to determine accurate distances out to cosmologically relevant distances and thus constrain the value of the Hubble constant. It also allows accurate distances to be measured to nearby galaxies, providing the luminosities of other scientifically interesting objects found in these galaxies and allowing quantitative investigations of the physics of these objects. One of the more elusive aspects of the PL relation is the effect that metallicity has on the luminosity of the Cepheids. It has long been argued that there is an offset in the luminosity depending on metallicity, but in spite of much effort there is still no unanimous agreement even on the sign of the effect. Storm et al. (2004) applied the near-infrared surface brightness method to Milky Way Cepheids and found that the slope of the resulting PL relation differed from that seen in Large Magellanic Cloud (LMC) PL relations, a finding that would have significant implications for the use of the relation as a distance indicator. Any improvement in our understanding of this relation is thus very important and has far-reaching consequences.

The near-infrared surface brightness method

The near-infrared surface brightness method takes advantage of the fact that a Cepheid star is radially pulsating. By observing the light curves in the visual and near-infrared (NIR), we determine the variation of *V*-band luminosity and (*V–K*) colour as a function of phase. These data can be used to determine the surface brightness of the star and thus the angular diameter as a function of phase. This relation is well established from interferometric observations of non-pulsating stars (Fouqué & Gieren, 1997) and was later confirmed by Kervella et al. (2004) by measurements of the angular diameters of Cepheids using the Very Large Telescope Interferometer (VLTI).

Observing the radial velocity curve for a star allows us to determine the pulsational velocity curve for that star by applying the so-called projection factor to the observed radial velocities. The projection factor accounts for the fact that the observed light from the radially pulsating star originates from the whole visible hemisphere of the star and not just the intercept between the stellar surface and the line connecting the observer and the stellar centre. From the pulsational velocity curve we can compute the variation of the stellar radius as a function of the phase. We thus have the angular diameter variation from the photometry and the corresponding absolute variation of the radius from the radial velocities. By relating the observed angular diameter, the radius of the star and the distance to the star geometrically we can solve the equations for the distance and the mean stellar radius. In this sense the method is similar to the Baade–Wesselink method for determining distances to pulsating stars.

In Figure 1 we plot the angular diameters against the radius variation with the best fit over-plotted for the LMC star HV877. For all our fits we disregard the phase interval between 0.8 and 1.0 where the star is contracting and the stellar atmospheres often exhibit signs of shocks (emission lines in the spectra) which can affect the angular diameter measurements. In the lower panel of Figure 1 the angular diameter is shown as a function of phase and it is clear that the match between photometric angular diameter (the dots) and the angular diameter inferred from the radial velocity curve and the best fit distance (the blue curve) agree rather well, except for the aforementioned phase region between 0.8 and 1.0.

The great advantage of the near-infrared surface brightness method over, e.g., trigonometric parallaxes, is the fact that it can be applied to stars in other galaxies as well as to nearby stars. The price to be paid is that the method is very demanding in observing time as precise light curves are necessary at both optical and near-infrared wavelengths as well as precise radial velocity curves.

A lot of data

Over the years a lot of data for Milky Way Cepheids has been collected by many workers in the field. This has allowed the near-infrared surface brightness method to be applied to many Galactic stars. The first application to a small sample of extragalactic (Small Magellanic Cloud [SMC]) Cepheids was successfully attempted by Storm et al. (2004). Gieren et al. (2005) then applied the method to a number of Cepheids in the LMC. The sample was still too small to delineate a definitive PL relation for the LMC and so we found it necessary to expand the

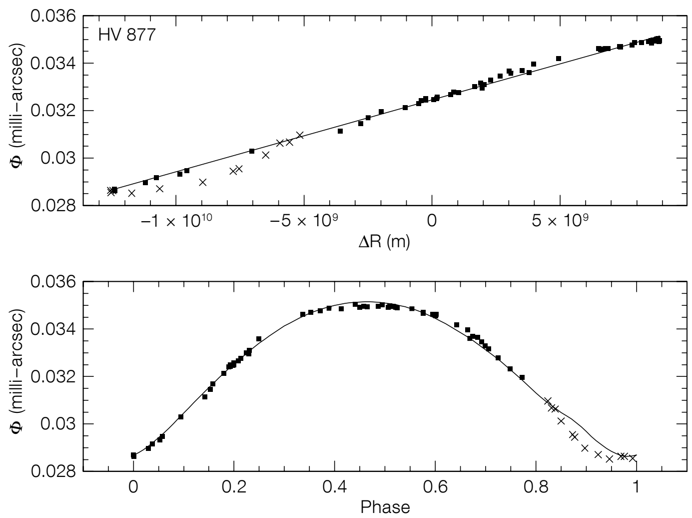

Figure 1. The upper panel shows the angular diameter versus the radius variation for the Cepheid HV877 with the best fit over-plotted. The lower panel shows the angular diameter as a function of phase. The phase interval from 0.8 to 1.0 is always omitted from the fit due to the possible presence of shocks in the stellar atmosphere.

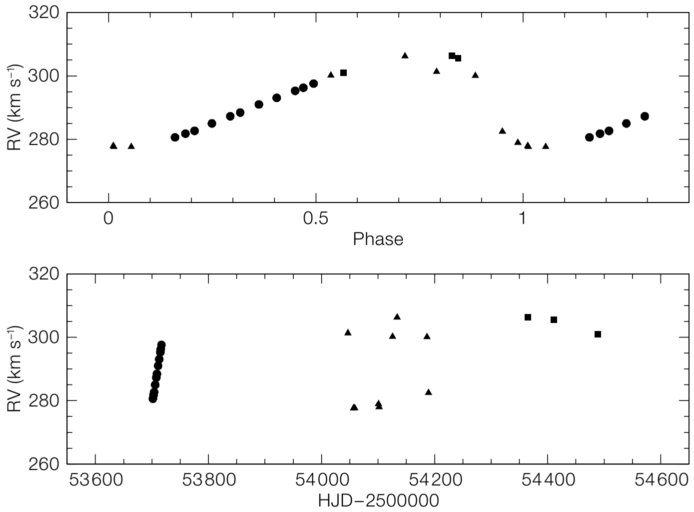

Figure 2. The upper panel shows the radial velocity curve for HV877 as observed with HARPS. In the lower panel the epochs of the individual observations are plotted. The different observing seasons have been coded by different symbols and the coding is the same in both panels.

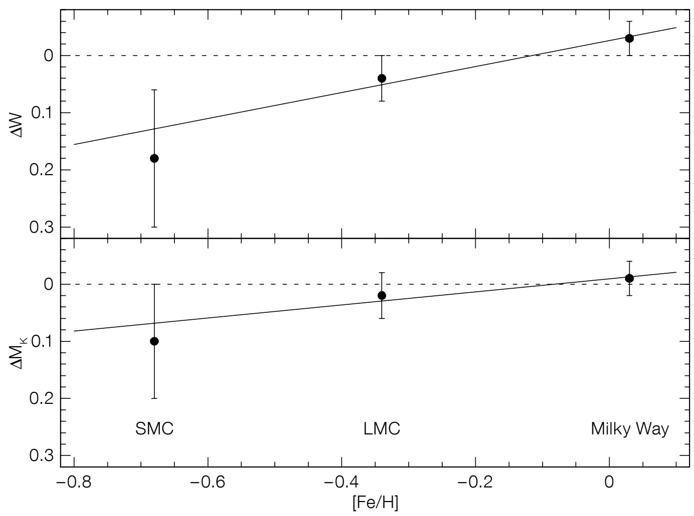

Figure 3. The zero-point offset of the PL relations in the *K*-band (lower panel) and in the Wesenheit index (upper panel). The three points correspond to the SMC, LMC, and Milky Way samples.

sample significantly. At this time new precise light curves in both the optical (Soszyński et al., 2008) and in the NIR (Persson et al., 2004) became available, so radial velocity curves were called for. We were granted time with HARPS on the 3.6-metre telescope at La Silla over three observing seasons. Over the first season we had 16 consecutive photometric (!) half-nights in which the shorter period stars were well covered; in the next seasons the observations were carried out in service mode with the diligent support of the La Silla staff.

In Figure 2 an example of a radial velocity curve is shown; again we have chosen the LMC Cepheid HV877 which has a pulsation period of 45.2 days. The good phase coverage is very important and the observations in the last two observing seasons were carefully planned to fill the gaps remaining from the first campaign. The lower panel in Figure 2 shows the timing of the observations, and it becomes obvious that this kind of work demands very careful scheduling to succeed and that the instrument is available not just in a few long blocks of time, but also for single observing blocks distributed throughout the semester. Thanks to the flexibility of the La Silla support staff the programme could be completed in three seasons. For our 20 target stars we obtained more than 450 data points with HARPS.

The effect of metallicity

With the new data in hand, we have determined luminosities for a total of 36 LMC Cepheids with periods ranging from 3 to 80 days and can determine a PL relation in any of the observed photometric bands (Storm et al., 2011b). For the Cepheids in the Milky Way we have proceeded in exactly the same fashion (Storm et al., 2011a), supplementing the available data with new radial velocity measurements from the echelle spectrograph on the STELLA robotic telescope on Tenerife, Spain and analysing a total of 70 fundamental mode Cepheids in a similar period range. It turns out that the slopes of the two samples are very similar and we do not find significant evidence that the slopes should be different. This is a very important point to establish when applying the PL relation as an extragalactic yardstick, especially as our earlier work suggested that such an effect was present. We then compare directly the luminosities of the stars from these two samples as well as the five Cepheids in the SMC, which we have re-analysed using the exact same procedure as for the other stars.

The resulting offset from the mean PL relation in the *K*-band and in the Wesenheit index from our study is shown in Figure 3 (in the lower and upper panels respectively). The Wesenheit index is a reddening-insensitive colour index based on the *V*- and *I*-band photometry, which has been employed in particular by the Hubble Space Telescope Key Project on the extragalactic distance scale (Freedman et al., 2001). We find a significant effect in the sense that metal-poor stars are fainter than metal-rich stars by 0.23 ± 0.1 mag per dex. The size of the effect is similar to the most recent one adopted by the Key Project group. This is a very reassuring result as our method is entirely independent from the methods that they have employed. In the case of the *K*-band, the effect is significantly (a factor of two) smaller and a null effect is consistent with the data. From the plot it is obvious that the constraint on the metallicity effect could be made even stronger by expanding the sample of SMC stars and thus decreasing the size of the error bar on this point. In fact this would probably provide the strongest constraint that is currently achievable.

The projection factor problem

In our first application of the method to Milky Way and SMC Cepheids, we could only determine the slope of the PL relation for the Milky Way sample, since the five SMC Cepheids all had about the same pulsation period. However, we found that the slope of the Milky Way PL relations differed significantly from the slopes of the PL relations obtained for LMC Cepheids, based on their apparent luminosity and assuming the same distance to all the LMC Cepheids. If this were to hold true, the PL relation would be a very poor extragalactic yardstick.

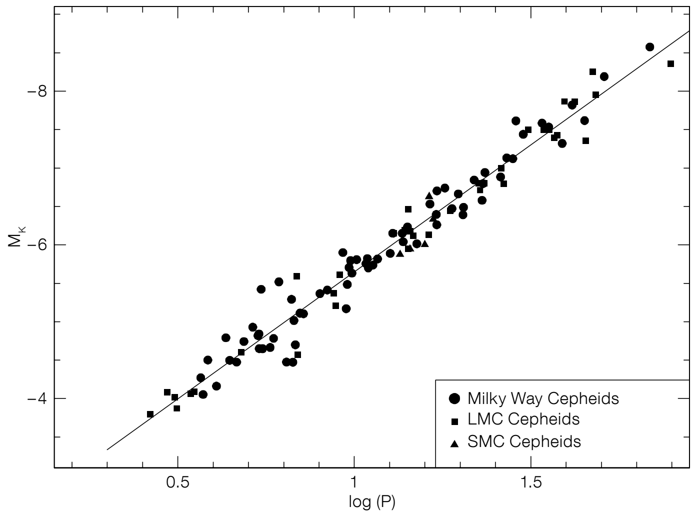

Figure 4. The universal *K*-band period–luminosity relation based on 111 Milky Way, LMC and SMC Cepheids is shown.

Gieren et al. (2005) applied the method to LMC Cepheids and found the first evidence that the slopes are in fact the same in both the Milky Way and in the LMC, but due to the availability of observations for only a few stars, the conclusion was not very firm. With the new data we confirm our findings from 2005, namely that the slopes are the same for the two samples, but the projection factor has a stronger period dependence than originally anticipated, or at least there is a period dependence of the method which earlier had not been accounted for. Using the Benedict et al. (2007) method, and taking trigonometric parallaxes for ten Cepheids to set the zero point and insisting that the distances we derive for LMC Cepheids are independent of pulsation period, we can well constrain the period effect and include it in the projection factor. Nardetto et al. (2011) and references therein discuss from a theoretical point of view the possible stellar atmosphere physics entering into the projection factor and they actually find a steeper relation than adopted in the past, albeit not as steep as we find from our purely empirical approach. This difference implies that there is some physics somewhere which is still not well understood.

The universal PL relation

With the modified projection factor from above and the knowledge that the effect of metallicity is very limited for metallicities between that of the SMC and the Milky Way, we can then combine the *K*-band luminosities for all 111 Cepheids from the Milky Way, the LMC and the SMC. In Figure 4 we show the relation. The dispersion is about 0.22 mag and is dominated by distance errors from our analysis. However the resulting relation is based on 111 stars so the slope and zero point are statistically very well-defined. The LMC Cepheids provide an LMC distance modulus of $(m\text{-}M)_o$ = 18.45 ± 0.04 mag.

Persson et al. (2004) found the dispersion for their LMC PL relation in the *K*-band to be less than 0.1 mag, so the *K*-band PL relation is an extremely powerful distance indicator, even for individual Cepheids. As the K-band is only weakly absorbed by interstellar dust and, as shown here, the PL-relation is only weakly dependent on metallicity, it has all the characteristics of an excellent distance indicator.

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Resolved Stellar Populations with MAD: Preparing for the Era of Extremely Large Telescopes

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Deep images in *J*, *H* and K_s filters using the Multi-conjugate Adaptive optics Demonstrator (MAD) on the VLT have been made of a region of the Large Magellanic Cloud near the globular cluster NGC 1928. Our aim was to assess if accurate photometry could be carried out down to faint limits over the whole MAD field of view. In addition we tested how accurate a basic analysis of the properties of the stellar population could be made using the near-infrared MAD photometry, compared to the Hubble Space Telescope optical photometry. This study has implications for understanding the issues involved in Extremely Large Telescope imaging of resolved stellar populations.

Archaeological evidence about the properties of individual stars over a large range of ages can tell us much about galaxy formation and evolution processes from the present day back to the early Universe. Low-mass stars have very long and passive lives and their photospheres hold time capsules of the gas from the interstellar medium out of which they formed. Thus populations of individual stars of a range of ages provide uniquely detailed information about the changing properties of galaxies: how the rate of star formation and chemical composition varied from its formation to the present day. Such studies can provide a link between the local Universe, high redshift surveys and theoretical simulations of galaxy formation and evolution.

A classical observational approach uses accurate multi-colour photometry of resolved stellar populations to create detailed colour–magnitude diagrams (CMDs), which can be interpreted using sophisticated statistical techniques. However this approach requires wide-field images with high, stable spatial resolution. In this respect the Hubble Space Telescope (HST) has revolutionised the photometric study of resolved stellar populations. However it remains a relatively small telescope, with a diffraction limit at optical wavelengths that is approached by the image quality of adaptive optics (AO) imagers working in the infrared on 8-metre-class ground-based telescopes. An AO imager on an Extremely Large Telescope (ELT) will of course lead to dramatic improvements in spatial resolution in the infrared.

At the moment most ground-based AO imagers are single guide star systems, which have very small fields of view with a strong variation in the point spread function (PSF) over this field. In order to be able to expand the field size and uniformity of the PSF, a technique called multi-conjugate adaptive optics (MCAO) is required. Here we describe an experiment with the prototype MCAO imager, MAD, at ESO's Very Large Telescope (VLT; see Marchetti et al. [2007] for details). It is anticipated that ELT imaging will be carried out with MCAO-fed imagers. ELTs are likely to be infrared (IR) optimised, using AO-based instrumentation (Gilmozzi & Spyromilio, 2007). This means that sensitive high-resolution ground-based imaging will only be possible at wavelengths starting from (perhaps) optical *I*-band, with a peak efficiency in the near-IR (NIR). Both sensitivity and spatial resolution are important for the study of resolved stellar populations, especially for compact galaxies and also for more distant galaxies beyond the Local Group. Hence it is valuable to carry out pilot studies in this wavelength range with the AO instruments available today.

NIR photometry does have several advantages: it can limit the effects of high and/or spatially variable extinction towards or inside a stellar field and it can also provide enhanced temperature sensitivity in a CMD, in particular when combined with optical bands. From theoretical evolutionary tracks we know that in an optical–IR CMD the features will be stretched out due to the long colour baseline. There exist robust techniques to make detailed analyses of observed CMDs by comparing them to theoretical models (e.g., Cignoni & Tosi, 2010). Whilst in the optical domain the theoretical stellar evolution models are well calibrated, in the NIR they still have to be fully verified for a range of stellar evolutionary phases. Moreover this aspect needs to be confirmed from an observational point of view using the actual photometric accuracies.

AO currently only works effectively at NIR wavelengths and this is likely to remain the case for the foreseeable future. This implies adapting current CMD analysis techniques, which are almost exclusively carried out at optical wavelengths. These changes bring several challenges to interpreting the images and the first step is to obtain useful *training* datasets.

Our MAD experiment

The Multi-conjugate Adaptive optics Demonstrator on the VLT has been employed to obtain deep images in *J*, *H* and K_s filters in a region of the Large Magellanic Cloud near the globular cluster NGC 1928. This field has previously been imaged at optical wavelengths by the Advanced Camera for Surveys (ACS) on HST. MAD, was mounted as visitor instrument on Unit Telescope 3 (UT3) at the VLT for three observing runs in 2007 and 2008. MAD is a demonstrator instrument built to prove the MCAO concept on the sky and is able to measure the atmospheric turbulence using three natural guide stars located, ideally, at the vertices of an equilateral triangle within a field of view of 2 arcminutes in diameter. This approach allows the turbulence to be corrected over the whole field of view (see Marchetti et al., 2006; 2007). The 2048 by 2048 pixel NIR detector available in MAD covered only a 1-arcminute square region of the full field of view, with 0.028-arcsecond square pixels. We used all three broadband filters available: *J*, *H* and K_s with total exposure times of 60 minutes in K_s, and 42 minutes in the *J* and *H* filters.

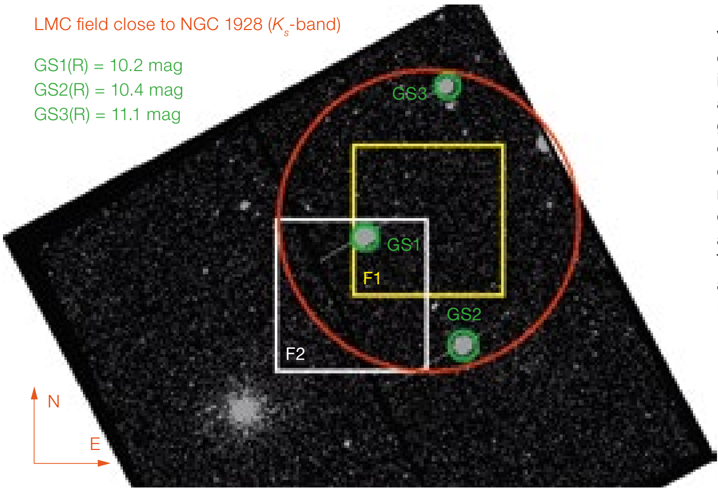


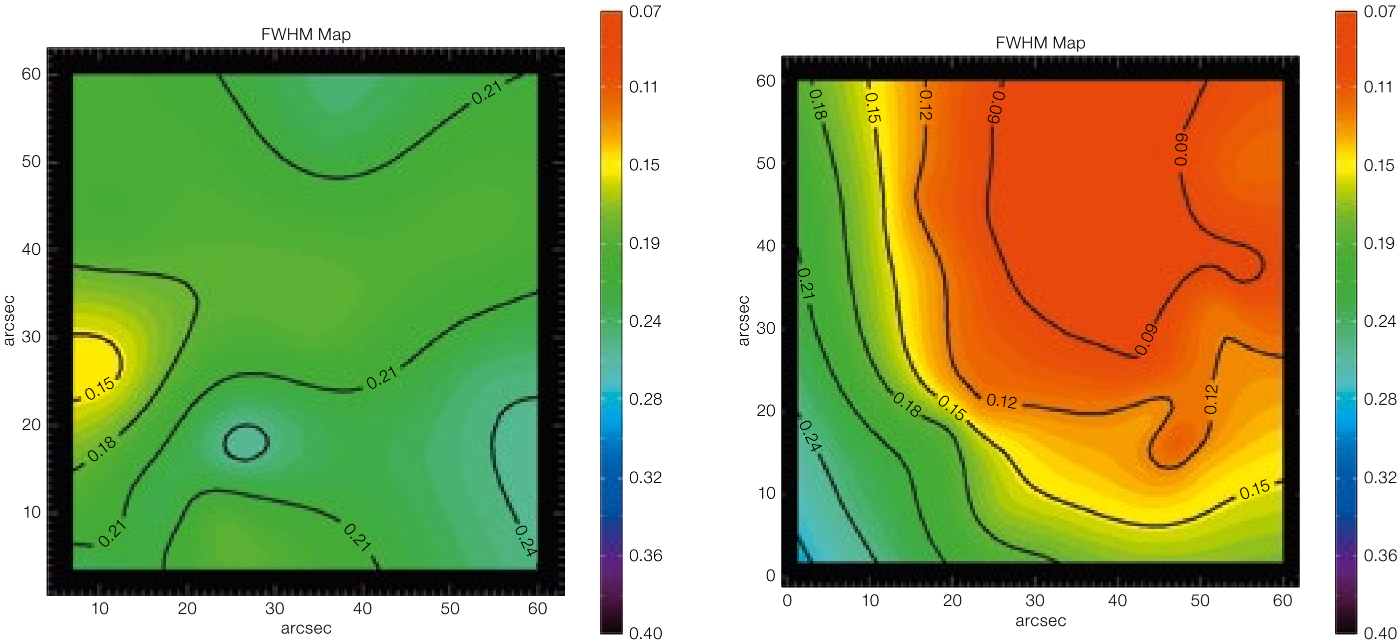
Figure 1. MAD field of view (yellow and white) on top of an ACS/HST image (from Mackey et al., 2004). The natural guide stars (green circles) are within a circle of diameter 2 arcminutes. The asterism is centred at RA = 05:21:11 and DEC = −69:27:32. The two pointings F1 and F2 are shown. From Fiorentino et al. (2011).

The MAD requirement of three bright natural guide stars within a circle of two arcminutes in diameter combined with our desire to image a region for which HST optical photometry was already available, limited the possible sky coverage. We found a suitable asterism in a region close to the Large Magellanic Cloud (LMC) globular cluster NGC 1928 (Figure 1). The area mapped by MAD observations is completely covered by ACS images (Mackey et al., 2004).

For our MAD images we estimated the stability of both the full width at half maximum (FWHM, see Figure 2) and the Strehl ratio of the PSF across the observed fields, using an IDL program provided by E. Marchetti. Despite the strong variation over the field, the best FWHM was achieved in field F2 (0.08 arcseconds) and it is close to the *H* filter diffraction limit (0.05 arcseconds). In contrast, the uniform PSF in field F1 only reaches a FWHM of 0.14 arcseconds, which is twice the K_s diffraction limit (0.07 arcseconds). The mean FWHM is 0.12 arcseconds for *H*-band and 0.20 arcseconds for the K_s-band. The Strehl ratio shows a similar spatial behaviour to the FWHM. The Strehl ratio in field F1 is quite uniform with values ranging from 5 to 15 % (in K_s-band), whereas this distribution varies rapidly in field F2 from 5 to 25 % (in *H*-band). The maximum Strehl ratios obtained in both fields reach, or even slightly exceed, the performance expected for MAD in "star-oriented" reference wavefront mode. As an example, the maximum Strehl ratio in K_s-band was predicted to be between 11 % and 24 % for seeing decreasing from 1.0 to 0.7 arcseconds.

MAD has been able to reach a FWHM of twice the diffraction limit in *H*- and K_s-bands at the large zenith distances typical of the LMC. The maximum Strehl ratio we have obtained in K_s-band is larger than 30 %, which is better than the expected performance (24 %) for MAD in "star-oriented" mode in our seeing conditions (seeing larger than 0.7 arcseconds). The uniformity and the stability of the correction varied not only with the position from the guide star asterism, but also with airmass and seeing conditions. The complex dependency of these factors prevented us from making a direct comparison between our results and other MAD studies. However, in other experiments MAD was successfully able to reach the diffraction limit in K_s-band (e.g., Falomo et al., 2009).

Figure 2. The FWHM variation (in arcseconds) measured across the field F1 (see Figure 1) in the K_s-band filter (left) and across the field F2 in the *H*-band filter (right). From Fiorentino et al. (2011).



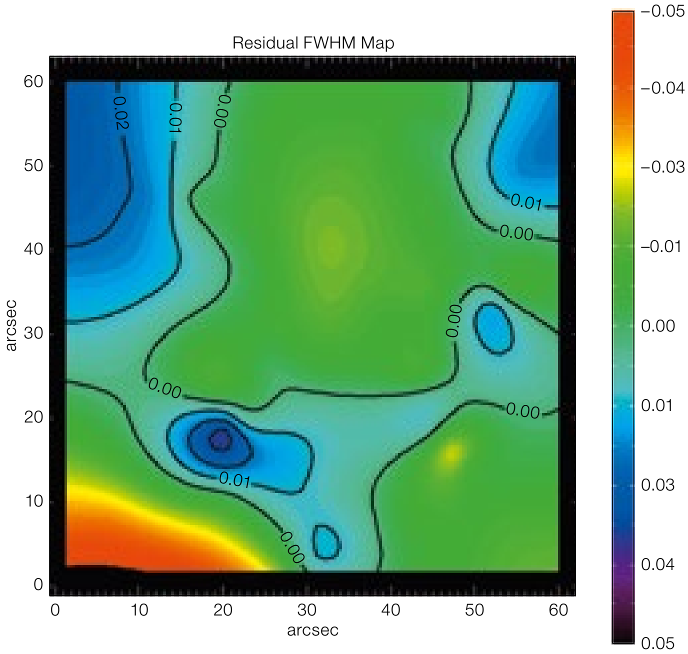


Figure 3. Residual map of the observed PSF *vs.* the model (in arcseconds) created with DAOPHOT for the challenging case of field F2 in *H*-band. From Fiorentino et al. (2011).

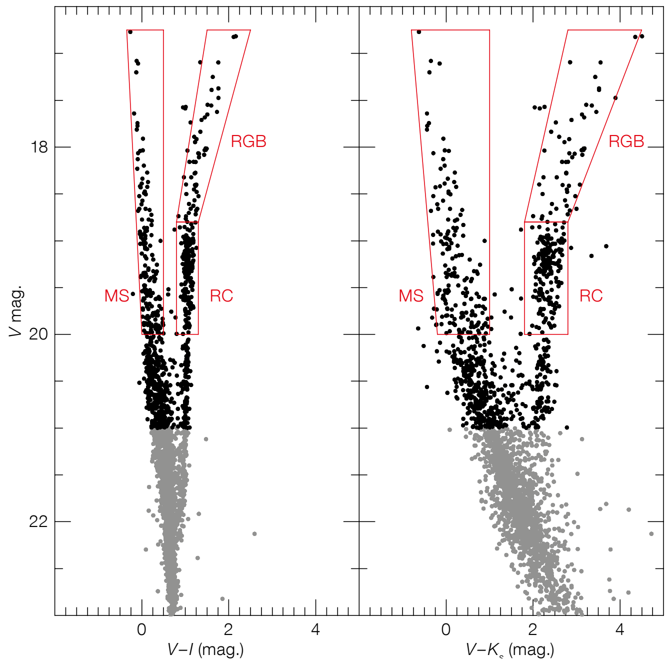


Figure 4. Colour–magnitude diagrams obtained combining purely optical *V*, *I* (from HST/ACS) and optical and near-infrared *V*, K_s (from HST/ACS and MAD) filters are shown at left and right (from Fiorentino et al., 2011). Red boxes are used to highlight the evolutionary phases considered in the CMD analysis, i.e. the Main Sequence (MS), the Red Clump (RC) and the Red Giant Branch (RGB).

The AO performance was so good that we were able to perform photometry using standard photometric packages, as DAOPHOT/ALLSTAR (Stetson, 1987; 1994). The approach is to model the PSF as the sum of a symmetric analytic bivariate function (typically a Lorentzian) and an empirical look-up table representing corrections to this analytic function computed from the observed brightness values within the average profile of several bright stars in the image. This hybrid PSF seems to offer adequate flexibility in modelling the complex PSFs that we found. Furthermore, the empirical look-up table makes it possible to account for the PSF variations (linear or quadratic) across the chip. We have compared the observed PSFs, and their variation over the field, with the PSF models created using DAOPHOT; an example is shown in Figure 3. Our experience in dealing with quite a large dataset of real MAD images (see Fiorentino et al. [2011] for details) suggests that a uniform correction is preferred to a very high, but non-uniform, Strehl ratio.

The colour–magnitude diagrams

The combination of optical and IR photometry is shown in Figure 4, (see Fiorentino et al. [2011] for all the filter combinations). The longest colour baseline to K_s-band stretches out the main CMD features (right panel) the most, hence allowing an easier and more precise separation of different stellar populations in all evolutionary phases. In Fiorentino et al. (2011), we performed a basic application of the well-established CMD synthesis methods to interpret our optical/IR CMDs in terms of a likely star formation history (SFH). The HST/ACS photometry is very deep (at least 4 mag below the Main Sequence Turn Off (MSTO), i.e. *V*, *I* ~ 26 mag) and the completeness is 100 % at the level of our faintest NIR observations. The set of synthetic populations (each with ~ 50 000 stars) that have been compared with our final catalogue have been simulated using the package IAC-STAR (Aparicio & Gallart, 2004), which generates synthetic CMDs for a given SFH and metallicity function. Composite stellar populations are calculated on a star-by-star basis, by computing the luminosity, effective temperature and gravity of each star by interpolation in the metallicity and age grid of a library of stellar evolution tracks.

Using our final optical/IR catalogue (*VIJHK*$_s$), where the optical observations come from ACS/HST, we could determine how well stellar evolution models in the different filter combinations match our data for the most likely SFH, derived by Holtzman et al. (1999) for a nearby field in the LMC. Given the uncertainties in the IR stellar evolution tracks, we pay special attention to comparing optical *vs.* infrared or purely infrared CMDs. We conclude that it is possible to apply the same techniques for determining SFHs in *V*- and *I*-bands to IR datasets, even if optical filters are clearly more accurate in this case. The optical/IR and purely IR analyses show the same trends, suggesting that the IR analysis could be improved, when deeper more accurate photometry will be available. Another key role for the IR analysis will be played by the theoretical calibration of IR stellar evolution tracks.

As by product of our analysis we could estimate the distance to the LMC by means of the infrared red clump method and we obtained 18.50 ± 0.06 (random error) ± 0.09 (systematic error), which is in very good agreement with distances measured with other independent methods.

Future prospects

We, among others (Bono et al., 2009; Ferraro et al., 2009; Campbell et al., 2010; Sana et al., 2010; and Fiorentino et al., 2011), have shown that the accurate and deep wide-field stellar photometry required to make detailed colour–magnitude diagrams is possible with MAD. Although MAD was a demonstrator instrument with a small engineering grade detector, the experiment worked very well. A future ELT will sample the atmospheric turbulence more accurately, which means that the peak correction achievable with MAD is smaller than that expected from an ELT. This means that future ELT MCAO instrumentation will be much more stable in terms of uniformity and performance (e.g., Deep et al., 2011).

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Colour image of the young open star cluster NGC 2100 situated in Large Magellanic Cloud taken with the EMMI instrument on the ESO New Technology Telescope (NTT) at the La Silla Observatory. Exposures in broad *B*-, *V*- and *R*-bands were combined with narrowband images centred on the emission lines of Hα, [N II] 6583 Å and [S II] 6716,6731 Å. Data for this image were selected by David Roma as part of the ESO Hidden Treasures competition. More details can be found in Release eso1133.

The Search for Intermediate-mass Black Holes in Globular Clusters

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Intermediate-mass black holes (IMBHs) fill the gap between supermassive and stellar-mass black holes and they could act as seeds for the rapid growth of supermassive black holes in early galaxy formation. Runaway collisions of massive stars in young and dense stellar clusters could have formed IMBHs that are still present in the centres of globular clusters. We have resolved the central dynamics of a number of globular clusters in our Galaxy using the FLAMES integral-field spectrograph at the VLT. Combining these data with photometry from HST and comparing them to analytic models, we can detect the rise in the velocity dispersion profile that indicates a central black hole. Our homogeneous sample of globular cluster integral-field spectroscopy allows a direct comparison between clusters with and without an IMBH.

The missing link?

Black holes have fascinated humanity for almost three centuries. Objects of pure gravity forming singularities in spacetime were first postulated by John Michell in 1783 and still seem enigmatic to physicists today, fuelling a strong drive to understand their nature, growth and evolution on all scales. Supermassive black holes (SMBHs) have masses from a million up to several billions of solar masses and are situated in the centres of massive galaxies. When a SMBH accretes the surrounding material it emits tremendous amounts of energy. This energy can be observed at all wavelengths and is detectable at large distances. The most active galaxies are quasars and have been a puzzle to astronomers since their discovery in the early 1960s. Their presence at large redshifts indicates that they existed at a time when the Universe was only one billion years old or less, at a very early stage of structure formation (Fan, 2006) when the first galaxies were just forming. How could a black hole with a mass of a billion or more solar masses have formed so early in the history of the Universe, when galaxies were not yet fully evolved?

Black holes can grow in two ways: through the accretion of surrounding material and by merging with other black holes. Even if a black hole accretes at the highest possible rate (the Eddington rate) for a billion years, it would not reach one million solar masses if it started with a one solar mass seed. Observations have also shown that SHMBs do not constantly accrete at the efficiency of the Eddington rate. Thus, the preferred process to explain the rapid growth of SMBHs is through the merger of smaller seed black holes of intermediate mass (between 100 and 10 000 solar masses, e.g., Ebisuzaki et al., 2001).

Numerical simulations have shown that intermediate-mass black holes can form in runaway mergers of stars in a dense environment, such as young star clusters. Also, ultraluminous X-ray sources at off-centre positions in galaxies provide strong evidence of massive black holes in stellar clusters (e.g., Soria et al., 2011). The globular clusters observed today are as old as their host galaxy: could they have delivered seed black holes, the missing link, in the crucial early stage of galaxy formation?

A further motivation for studying IMBHs is that observations have shown a correlation between the masses of SMBHs and the velocity dispersion of their host galaxies (see Figure 1 and e.g., Ferrarese & Merritt, 2000; and Gebhardt et al., 2000). Extrapolating this relation to the mass ranges of IMBHs yields a velocity dispersion of between 10 and 20 km/s, such as those observed from the stars in globular clusters. The origin and interpretation of this relation is still under debate and it is not known whether it

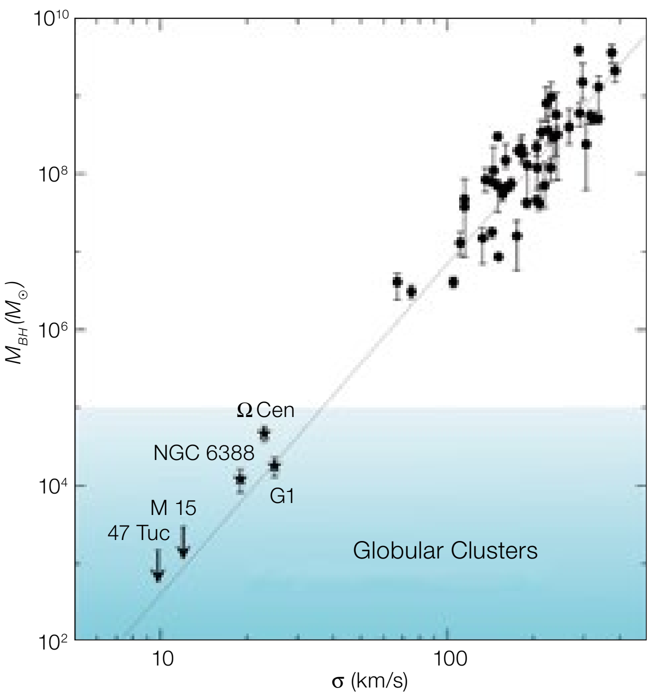

Figure 1. The M_{BH}– σ relation for supermassive black holes in galaxies is shown. Globular clusters and dwarf galaxies lie at the extrapolation of the relation towards lower black hole masses. The points for a few globular clusters are plotted.

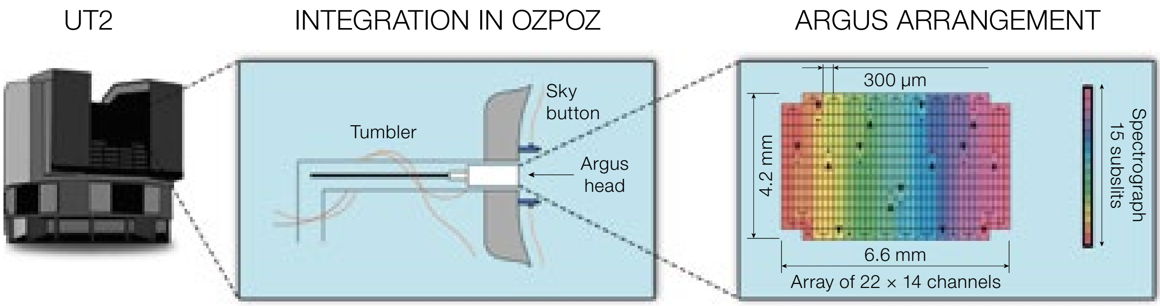

Figure 2. A schematic of the VLT FLAMES ARGUS integral field unit in the Ozpoz fibre positioner is shown (centre). The ARGUS fibre geometry and the allocation of fibres into sub-slits feeding the GIRAFFE spectrometer is shown at right.

truly holds at the lower mass end. The study of IMBHs and their environments might shed light on many astrophysical problems, helping us to develop a better understanding of black hole formation and galaxy evolution.

The idea that IMBHs might exist in globular clusters was first proposed decades ago. Many observational attempts to find direct evidence of a black hole in globular clusters have followed. However, most studies have only observed the light profiles in the centre of the clusters and compared these with models. A central black hole does produce a prominent cusp in the surface brightness profile of a globular cluster (Bahcall & Wolf, 1976; Baumgardt et al., 2005), but this signature can be confused with the one expected from a core-collapse process. For this reason, it is crucial to study the kinematic profile in addition to the light profile.

Our group set out to search for the kinematic signatures of intermediate-mass black holes in Galactic globular clusters by trying to understand which of our observed globular clusters host an intermediate-mass black hole at their centre and which do not. With a sample of ten clusters, our goal is to understand whether the presence of an IMBH correlates with any of the cluster properties.

Mapping the integrated light

A central black hole in a dense stellar system, such as a globular cluster, affects the velocities of its surrounding stars. As an additional gravitational potential it causes the stars in its vicinity to move faster than expected from the gravitational potential of the cluster itself. Measuring this difference provides an estimate of the mass of the possible black hole. Obtaining velocities and velocity dispersions in the centres of globular clusters, however, is very difficult due to the high stellar densities in these regions. Resolving individual stars in the centre and measuring spectra with ground-based telescopes requires adaptive optics, extraordinary weather conditions and time-consuming observations. For these reasons we used a different method — integrated light measurements (Noyola, 2010; Lützgendorf, 2011).

We used the large integral field unit ARGUS, a mode of the FLAMES facility mounted on Unit Telescope 2 of the Very Large Telescope (VLT). Figure 2 shows schematically the properties of the instrument. ARGUS consists of a 22 × 14 array of microlenses (called spaxels for **spa**tial pi**xels**) with a sampling of 0.52 arcseconds per microlens and a total aperture of 11.5 by 7.3 arcseconds on the sky; this field allows the core of a globular cluster to be covered in a few pointings. A more detailed description of FLAMES and the ARGUS mode can be found in Pasquini (2002) and Kaufer (2003). For the observations the GIRAFFE spectrograph was set to the low spectral resolution mode LR8 (coverage 820–940 nm at a spectral resolution of 10 400) and the ARGUS unit was pointed to different positions, each of them containing three exposures of 600 s with 0.5 arcsecond dithering, to cover the entire core radius. The position angle of the long axis of the integral field unit was varied from 0 to 135 degrees in order to achieve maximum coverage of the cluster centre.

Figure 3 shows the combined pointings from the ARGUS observations of the cluster NGC 2808 together with the reconstructed field of view on the Hubble Space Telescope (HST) image. The HST images were obtained with the Wide Field and Planetary Camera 2 (WFPC2) in the *I*-band (F814W) filter in May 1998 (GO-6804, PI: F. Fusi Pecci) and retrieved from the European HST archive. The choice of filter is related to our spectral observations, which are obtained in the wavelength range of the calcium triplet, a prominent absorption feature around 860 nm and ideally suited to the measurement of radial velocities. By measuring the relative shift of the calcium triplet through absorption line fitting, we obtained a velocity for each spectrum. The final velocity map for NGC 2808 is also shown in Figure 3. Velocity maps are instructive to look at and good for identifying suspicious features, but in order to compare our data to model predictions we need the velocity dispersion profile. It is the velocity dispersion σ, or the second moment of the velocity (the quadratic sum of the expectation value of the velocity and the velocity dispersion), which holds information about the mass distribution.

In order to derive a velocity dispersion profile, we used radial bins around the centre of the cluster and combined all the spectra included in each bin. The absorption lines of the resulting spectra are broadened due to the different velocities of the individual stars contributing to the spaxels. Measuring the width of these lines yields the velocity dispersion for each bin, thus a velocity dispersion profile as a function of radius. Great care is taken to measure the true velocity dispersion and not artefacts of the instrument, the data reduction or the data combination process.

Black hole hunting

A black hole is suspected when we see a difference between the measured ve-

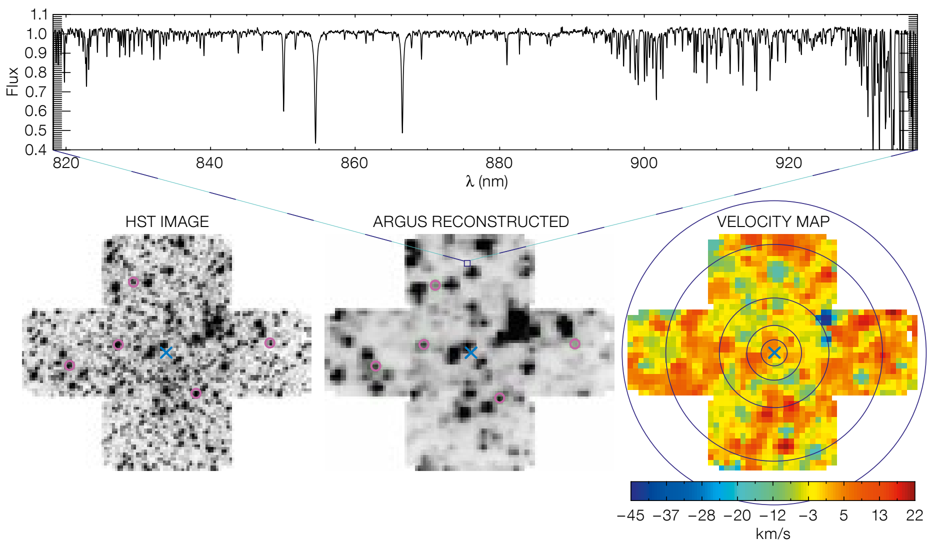

Figure 3. The process of deriving a velocity dispersion profile with integral-field spectroscopy is illustrated. Shown are the field of view on the HST image (left panel), the ARGUS reconstructed pointing (middle panel), a datacube with each spaxel (spatial element) being a spectrum in the calcium triplet region (shown above), and the resulting velocity map (right panel). The circles indicate the bins applied to derive the velocity dispersion profile.

locities and the expected velocities from the gravitational potential of the cluster derived from its light distribution only. In order to determine these expected velocities, we needed an estimate of the stellar density in the cluster. This is done by taking images from HST and measuring the surface brightness profile. We determined the photometric centre of the cluster by measuring the symmetry point of the spatial distribution of the stars. Using colour–magnitude diagrams, we also identified the stars which do not belong to the cluster.

In addition to the VLT and HST observations, data from other instruments are required for kinematic measurements of outer regions that are too faint to be studied using integrated light. In order to detect a black hole, only the innermost points are critical, but in order to understand the global dynamics of the cluster and to determine its mass, the entire velocity dispersion profile is needed. The outer kinematics can be obtained through the measurement of individual stars, since the density of stars is lower than in the centre. The instruments we used to obtain the outer kinematics are the Rutgers Fabry Perot on the Blanco 4-metre telescope at Cerro Tololo Inter-American Observatory (CTIO) and multi-object spectrographs such as FLAMES/Medusa. A Fabry Perot instrument can also operate as an integral field unit: narrow wavelength band, wide-field images at a series of different wavelength steps are recorded. This results in a set of images with high spatial resolution from which the stellar absorption line features can be extracted by combining the photometry of the objects from each wavelength bin (Gebhardt et al., 1992).

After deriving the full kinematic and photometric profiles, the information is fed into models. We use different kinds of models. The first and the simplest kind are analytical Jeans models. The models take the surface brightness profile, deproject it into a three-dimensional density profile and predict a velocity dispersion profile. The latter is then compared to the actual measured velocity dispersion profile. We study the variations of the model when including the additional gravitational potential of a black hole into the equations. By trying different black hole

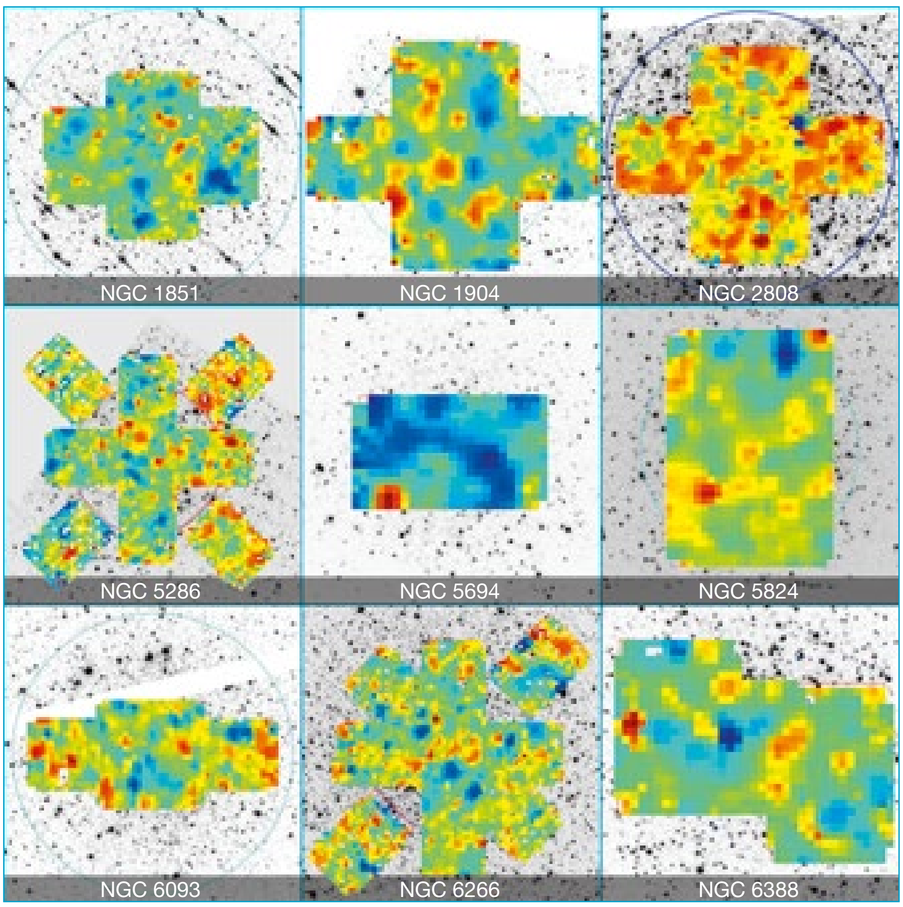

Figure 4. Velocity maps of all the Galactic globular clusters of our sample (except Omega Centauri) are shown superposed on HST images.

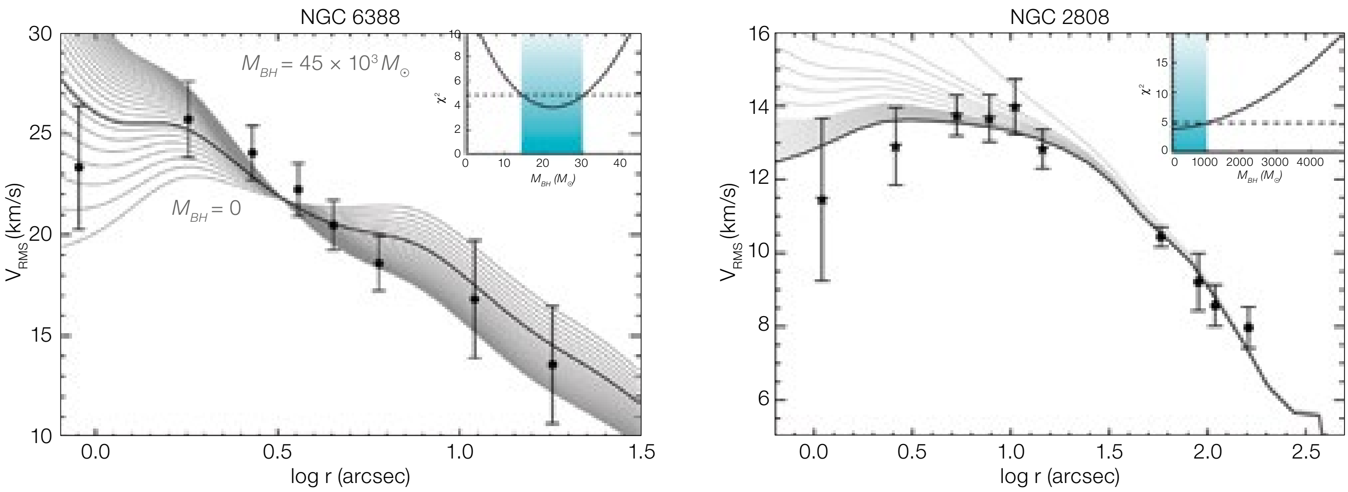

Figure 5. The velocity dispersion profiles of the globular clusters NGC 6388 and NGC 2808 are shown. Overplotted are a set of Jeans models with different black hole masses (grey lines) and the best-fit model (black line). In the corner of each plot the variation of χ^2 of the fit as a function of black-hole mass is shown. The shaded area marks the region for $\Delta\chi^2 < 1$, and thus the 1σ error on the black hole mass. While for NGC 2808 the profile is rather flat and does not require a black hole, NGC 6388 has a steeper profile and a best-fit model with a ~ 17 000 $M_\odot$ black hole (Lützgendorf et al., 2011, Lützgendorf et al., 2012, in prep.).

masses, we find which model fits our data best. Figure 5 shows the entire velocity dispersion profile for two examples: NGC 2808 and NGC 6388 with a set of Jeans models overplotted. A central black hole causes a rise in the velocity dispersion profile. In the case of NGC 2808 no black hole is needed in order to explain the observed data but in the case of NGC 6388 the profile shows a clear rise, making this cluster an excellent candidate for hosting an intermediate-mass black hole.

In addition to these analytical models, N-body simulations are employed in order to reproduce the observations (Jalali et al., 2011). This approach is crucial in order to exclude alternative scenarios which could cause a kinematic signature similar to a black hole, such as a cluster of dark remnants (e.g., neutron stars). N-body simulations are ideally suited for globular clusters since their kinematics are only determined by the motions of their stars/particles. Assuming certain initial conditions, the stars are distributed in space according to a mass function (i.e., luminosities) and are assigned velocities. Then, the system evolves by letting the particles interact gravitationally. By following the evolution of this cluster over a lifetime (~ 12 Gyr), we studied its evolution in detail and compared the final state with the observations. By changing the initial conditions, we found the simulations which fitted the observed data best and learnt about the intrinsic properties of the globular clusters and their black holes, such as mass-to-light ratio variations and the anisotropy in the cluster.

Black hole or no black hole?

Our sample, so far, includes ten Galactic globular clusters observed in 2010 and 2011, including the pilot project target Omega Centauri. All of them have been analysed and velocity maps have been computed (see Figure 4 for all the clusters except Omega Centauri). Modelling all the clusters, however, is not straightforward as each cluster shows peculiarities: some show very shallow kinematic profiles, while others seem to have multiple centres — one photometric and one kinematic.

However, for most of the clusters we are confident that we can determine from the central kinematics whether they are likely to host an intermediate-mass black hole or not and that good constraints on their masses can be provided. The two examples in Figure 5 show that in the case of NGC 6388 a model with a black hole of ~ 17 000 $M_\odot$ is needed to reproduce the data, while the velocity dispersion profile in the core of NGC 2808 is rather flat and an IMBH larger than ~ 1000 $M_\odot$ is excluded. Among all our candidates we find clusters like NGC 2808 as well as clusters where the central points of the velocity dispersion profile are rising just as in NGC 6388 and Omega Centauri.

After finalising the analysis and the modelling of all the clusters in our sample, we will be able to start correlating the presence and mass of an IMBH with the cluster properties. We will also be able to set the selection criteria for further studies and use our experience and expertise to extend the search for IMBHs to more distant objects and larger samples. This strategy will advance our knowledge of globular cluster formation and evolution and bring us closer to an understanding of black hole growth and galaxy formation.

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The Gaia-ESO Public Spectroscopic Survey

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The Gaia-ESO Public Spectroscopic Survey has begun and will obtain high quality spectroscopy of some 100 000 Milky Way stars, in the field and in open clusters, down to magnitude 19, systematically covering all the major components of the Milky Way. This survey will provide the first homogeneous overview of the distributions of kinematics and chemical element abundances in the Galaxy. The motivation, organisation and implementation of the Gaia-ESO Survey are described, emphasising the complementarity with the ESA Gaia mission. Spectra from the very first observing run of the survey are presented.

"*Europe has led the way in Galactic research as regards astrometry and spectroscopy, and is on the brink of taking the lead in photometry: ESA's Hipparcos mission pioneered space astrometry and paved the way for the ambitious Gaia mission, which will perform the first parallax survey down to magnitude* V *= 20 in parallel with a complete characterisation of each observed object; ESO's innovative telescopes (NTT and VLT) coupled to leading capabilities in the construction of multi-object spectrographs have yielded detailed stellar abundances of faint stars; ESO is about to start massive programmes of optical/near-IR photometry with two dedicated survey telescopes (VISTA and VST).*" That impressive long sentence introduced the *Messenger* article (Turon et al., 2008b) describing the work of the ESA–ESO Working Group on Galactic Populations, Chemistry and Dynamics (Turon et al., 2008a). The same *Messenger* issue reported on the ASTRONET Infrastructure Roadmap: A Twenty Year Strategy for European Astronomy (Bode & Monnet, 2008), which concluded "*among medium-scale investments, science analysis and exploitation for the approved Horizon 2000 Plus astrometric mission Gaia was judged most important*". The ESO community and ESO's Scientific Technical Committee (STC) have continued the theme, leading to an ESO Workshop on Wide-field Spectroscopic Surveys, held in March 2009 (Melnick et al., 2009). This meeting concluded that a large public spectroscopic survey, using current ESO VLT instrumentation, "*could place the European community in a favourable situation ... and would go a long way towards generating the data required to complement Gaia if the surveys begin soon*".

That recommendation led, via a process involving Letters of Intent, review, and preliminary selection, to a 300-author proposal for the Gaia-ESO Public Spectroscopic Survey, a 300-night survey of all Galactic Stellar Populations, using FLAMES (both GIRAFFE and UVES) on the VLT's Unit Telescope 2 (UT2). Following the review and approval of the proposal, and the development of a detailed Survey Management Plan agreed between ESO and the two Co-PIs, the Gaia-ESO Survey began taking data on the night of 31 December 2011.

This ambitious survey, of similar scale to the Public Surveys on VISTA and VST, is very clearly the culmination of many years of hard work, initiative, planning and dedication by very many people, from the writing of the science strategy to the spectrum analysis software. With the European Space Agency Gaia mission due for launch in 2013, Europe is indeed well on the way to scientific leadership in quantitative studies of the formation and evolution of the Milky Way and its components. The Gaia-ESO Survey offers the opportunity to meet that challenge.

What is the Gaia-ESO Survey?

The Gaia-ESO Public Spectroscopic Survey employs the VLT FLAMES instrument for high quality spectroscopy of some 100 000 stars in the Milky Way. With well-defined samples, based primarily on current VISTA photometry for the field stars, and on the Two Micron All Sky Survey (2MASS) and a variety of photometric surveys of open clusters, the survey will quantify the kinematic multi-chemical element abundance distribution functions of the Milky Way Bulge, the thick Disc, the thin Disc, and the Halo stellar components, as well as a very significant sample of 100 open clusters, covering all accessible cluster ages and stellar masses. This alone will revolutionise knowledge of Galactic and stellar evolution. When combined with precision astrometry, delivering accurate distances, 3D spatial distributions, 3D space motions, and improved astrophysical parameters for each star, the survey will quantify the formation history and evolution of young, mature and ancient Galactic populations. The precision astrometry will be provided by the Gaia "Galactic census", with the first astrometric data release likely to occur in 2016, in time for the full analysis of the complete Gaia-ESO Survey data.

The Gaia-ESO Survey is among the largest and most ambitious ground-based surveys ever attempted by European astronomy. The Survey consortium involves some 300 scientists in over 90 institutions (see the list of team members). This large allocation of telescope time, which followed a very detailed scientific and managerial peer review, is a robust measure of the strength and originality of the scientific case, the high legacy value of the Survey dataset, the appropriateness of the methodology being utilised, and the project implementation and management structure. There are two survey Co-PIs, Gerry Gilmore and Sofia Randich, leading the Milky Way and calibration aspects, and star cluster aspects, respectively. The important synergy from covering all Galactic components is a joint responsibility and opportunity.

Gaia-ESO Survey scientific background

Understanding how galaxies actually form and evolve within our ΛCDM (Lambda Cold Dark Matter) Universe, and how their component stars and stellar populations form and evolve, continues to be an enormous challenge. Extant simulations of the aggregation of cold dark matter (CDM) suggest that galaxies grow through a sequence of merger and accretion events. Most events involve accretion of an object that is so small that it barely perturbs the system, some events involve an object large enough to produce a mild perturbation, and a handful of events involve an object that causes a major convulsion. Exactly how these events impact on a galaxy cannot be predicted at this time because the extremely complex physics of baryons cannot be reliably simulated: at a minimum it involves interstellar chemistry, magnetic reconnection, radiative transfer in the presence of spectral lines and significant velocity gradients, thermonuclear fusion, neutron absorption, neutrino scattering, radioactive decay, cosmic ray acceleration and diffusion. Theoretical models of galaxy formation rely more heavily on phenomenological models than on physical theory. Thus, these models require calibration with well-studied (nearby) test cases. For example, star formation involves turbulence, magnetic reconnection, collisionless shocks, and radiative transfer through a turbulent medium. Similarly, the treatment of convection, mixing, equations of state at high density, opacities, rotation and magnetic fields can all significantly affect stellar luminosities, radii, and lifetimes at different evolutionary phases. We are far from being able to simulate the coupled evolution of CDM and baryons from *ab initio* physics.

Observations are crucial to learning how galaxies and stars were formed and evolved to their present structure. Observations of objects at high redshifts and long lookback times are important for this endeavour, as is the detailed examination of our Galaxy, because such "near-field cosmology" gives insights into key processes that cannot be obtained by studying faint, poorly resolved objects with uncertain features. Just as the history of life was deduced by examining rocks, we expect to deduce the history of the Galaxy by examining stars. Stars record the past in their ages, compositions and kinematics. For example, individual accretion and cluster dissolution events can be inferred by detecting stellar streams from accurate phase-space positions. Correlations between the chemical compositions and kinematics of field stars will enable us to deduce the history of star formation and even the past dynamics of the Disc. The kinematic structure of the Bulge will reveal the relative importance in its formation of disc instability and an early major merger. The study of open clusters is crucial to understanding fundamental issues in stellar evolution, the star formation process, and the assembly and evolution of the Milky Way thin Disc.

Most stars form in associations and clusters, rather than singly, so understanding star formation also implies studying cluster formation. Advances in infrared astronomy have opened up the study of the formation of stellar cores in dark

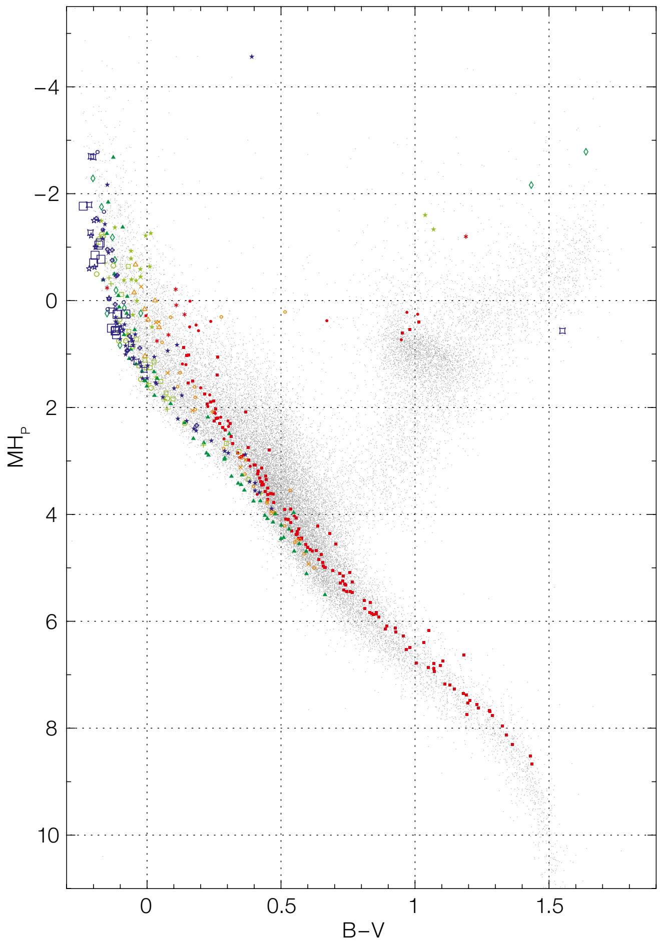


Figure 1. A colour–magnitude diagram based on the Hipparcos re-analysis by Floor van Leeuwen, of nearby precise luminosity and colour data. The open cluster data are colour-coded by age, blue being younger, red older. Local field stars are in grey.

clouds, and the period in which a core grows by accretion. We know that outflows of various types disperse most of the gas of a cloud, and that the great majority of groups of young stars then quickly disperse. More populous groups survive the dispersal as open clusters, and subsequently disperse through a combination of internal mass loss, two-body scattering off other members of the group, and tidal disturbance by the gravitational fields of external objects such as giant molecular clouds and spiral arms. It is possible that open clusters are the dominant source of field stars. They trace different thin Disc components covering broad age and metallicity intervals, from a few Myr up to several Gyr, from 0.3 to two times solar abundance. Each cluster provides a snapshot of stellar evolution. Thus, observations of many clusters at different ages and chemical compositions, quantify stellar evolution, allowing increasingly detailed theoretical models to be tested. Much stellar and Galactic astrophysics hinges on these crucial comparisons between cluster observations and the predictions of the models.

Figure 1 illustrates the state-of-the-art colour–magnitude diagram based on a re-analysis of Hipparcos data (van Leeuwen, 2007) for nearby stars. The rich information content of precise stellar astrometric, kinematic, and chemical abundance data for both clusters and field quantifies not only stellar evolution models, and their limitations, but also Galactic evolution models, and their limitations. Adding 100 well-observed clusters, covering and characterising stars down to low masses, to this figure will be a revolution in our knowledge.

Scale of the challenge and specific scientific objectives

The key to addressing these topics, and decoding the history of the formation and

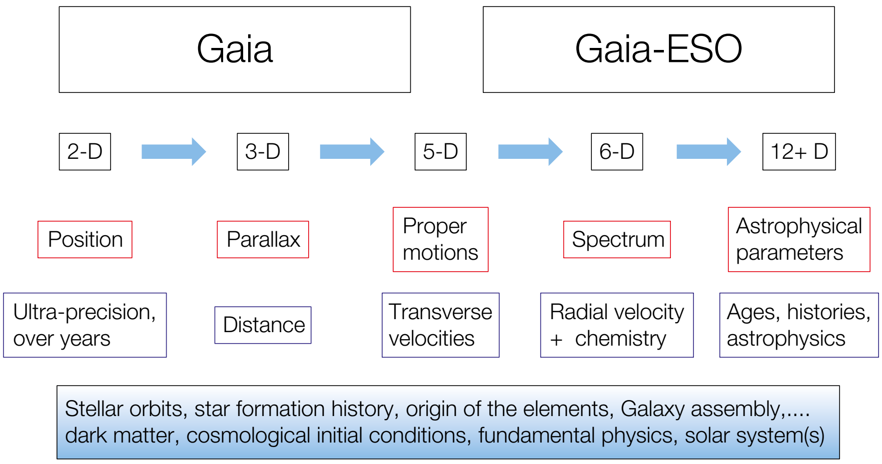


Figure 2. Diagrammatic representation of the outputs of the Gaia and Gaia-ESO surveys, showing how they are complementary.

evolution of the Galaxy and its components, involves three aspects: chemical element mapping, which quantifies timescales, mixing and accretion length scales, star formation histories, nucleosynthesis and internal processes in stars; spatial distributions, which relate to structures and gradients; and kinematics, which relates to both the felt, but unseen, dark matter, and dynamical histories of clusters and merger events. With Gaia, and stellar models calibrated on clusters, one will also add ages for (slightly evolved) field stars, for the first time. Manifestly, a spectroscopic survey returning data for very large samples is required to define with high statistical significance all these distribution functions and their spatial and temporal gradients.

The Gaia-ESO Survey is that survey. Moreover, it will also be the first survey yielding a homogeneous dataset for large samples of both field and cluster stars, providing unique added value. The specific top-level scientific goals it will allow to be addressed include:
- Open cluster formation, evolution, and disruption;
- Calibration of the complex physics that affects stellar evolution;
- Quantitative studies of Halo substructure, dark matter, and rare stars;
- Nature of the Bulge;
- Origin of the thick Disc;
- Formation, evolution, structure of the thin Disc;
- Kinematic multi-element distribution function in the Solar Neighbourhood.

Gaia-ESO Survey legacy overview

This VLT survey delivers the data to support a wide variety of studies of stellar populations, the evolution of dynamical systems, and stellar evolution. The Survey will complement Gaia by using the GIRAFFE+ UVES spectrographs to measure detailed abundances for at least 12 elements (Na, Mg, Si, Ca, Ti, V, Cr, Mn, Fe, Co, Sr, Zr, Ba) in up to 10 000 field stars with $V < 15$ mag and for several additional elements (including Li) for more metal-rich cluster stars. Depending on target signal-to-noise (S/N) and astrophysical parameters, the data will typically probe the fundamental nucleosynthetic channels: nuclear statistical equilibrium (through V, Cr, Mn, Fe, Co), and alpha-chain (through Si, Ca, Ti). The radial velocity precision for this sample will be 0.1 to 5 kms^{-1}, depending on target, with, in each case, the measurement precision being that required for the relevant astrophysical analysis. The data will resolve the full phase-space distributions for large stellar samples in clusters, making it possible to identify, on both chemical and kinematic grounds, substructures that bear witness to particular merger or starburst events, and to follow the dissolution of clusters and the Galactic migration of field stars.

The survey will also supply homogeneously determined chemical abundances, rotation rates and diagnostics of magnetic activity and accretion, for large samples of stars in clusters with precise distances, which can be used to challenge stellar evolution models. Considerable effort will be invested in abundance calibration and ESO archive re-analysis to ensure maximum future utility.

Why not just wait for Gaia?

The Gaia mission will provide photometry and astrometry of unprecedented precision for most stars brighter than $G = 20$ mag, and obtain low resolution spectra for most stars brighter than 17th magnitude. The first astrometry data release is likely to be in 2016, with spectrophotometry and stellar parameters to follow later, and 2021 for the final catalogue. Crucially, Gaia has limited spectroscopic capabilities and, like all spacecraft, does not try to compete with large ground-based telescopes at what they do best.

A convenient way of picturing the Gaia–ground complementarity is to look at the dimensionality of data which can be obtained on an astrophysical object. Larger amounts of information of higher quality are the goal, to increase understanding. Figure 2 gives a cartoon view of this information set. There are four basic thresholds which we must pass. The first is to know a source exists, its position, and basic photometric data. Photometric surveys, such as those underway at VISTA and VST will deliver this information. The second is to add the time domain — motions, including parallax, providing distances and speeds. Here Gaia will be revolutionary. The third threshold is radial velocity, turning motions into orbits. While Gaia will provide radial velocities, the magnitude limit is three magnitudes brighter than that of the astrometry and the precision is much below that of proper motions. Here the Gaia-ESO will be crucial to supplement Gaia spectroscopy. The fourth threshold is chemistry, and astrophysical parameters. These latter two both require spectroscopy, which is the key information from the Gaia-ESO Survey.

Gaia-ESO Survey samples and observational strategy

The Gaia-ESO Survey observing strategy has been designed to deliver the top-level survey goals. The Galactic inner and outer Bulge will be surveyed, as will be the inner and outer thick and thin

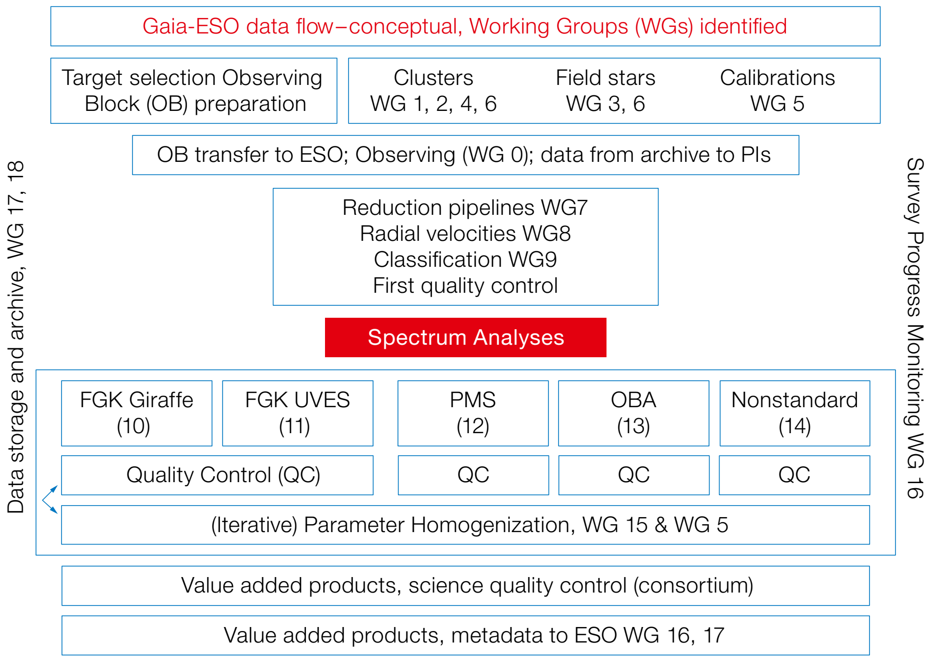


Figure 3. Data flow schematic, from the Survey Management Plan, to illustrate the challenges involved in the Gaia-ESO Survey. The logical path flows from pre-observation target selection through observing at the top, through data processing, data spectrum analysis, astrophysical parameter determination, calibration, homogenisation, to delivery of science data for verification analysis at the bottom. Infrastructure provision is down the sides, being relevant at all stages, as is the survey progress monitoring, and quality control by the Co-PI teams, preparatory for public data release.

Discs, the Halo and known Halo streams. Particular focus will be put on the local thin Disc, as this study both complements Gaia astrometry and will benefit most from the high precision Gaia data. More specifically, prime GIRAFFE targets in the Bulge are K giants, which dominate the relevant colour–magnitude diagram selection. Primary targets in the Halo and thick Disc are r = 17–18 mag. F stars, with the bluer, fainter F stars probing the Halo and brighter, redder F stars probing the thick Disc. Sloan Digital Sky Survey (SDSS) photometry shows a clear thick Disc/Halo transition at $17 < r < 18$ and $0.2 < g - r < 0.4$ — and we use the equivalent selection from VISTA near-infrared photometry. In fields crossing known Halo streams (e.g., Sagittarius), K giant candidates will be included in the sample.

Outer thick Disc fields will have distant F stars as prime targets, like the Halo. This well-defined low latitude sample probes 2–4 kpc, more than a radial scale length. In addition, we will allocate 25 % of the fibres to brighter candidate K giants, which probe the far outer thick Disc, warp, flare and Monocerus stream, and will deliver excellent S/N. To quantify thin Disc dynamics, we will target 4–6 fields to I = 19 mag. in the Plane to test spiral arm/bar dynamics obtaining several thousand radial velocities per line of sight. We will dedicate UVES parallels for the field surveys to an unbiased sample of 5000 FG stars within 2 kpc of the Sun.

Cluster selection is optimised to fine-sample the age–[Fe/H]–Galactocentric distance–mass parameter space. Clusters in all phases of evolution (except embedded), with ages from about 1 Myr up to 10 Gyr will be included, sampling different environments and star formation conditions. This will provide sufficient statistics to explore the dynamical evolution of clusters; the same sample will map stellar evolution as a function of metallicity for $0.1 < M/M_{\odot} < 100$, even for short-lived evolutionary phases, and provide a population large enough to throughly investigate metallicity as a function of Galactocentric radius and age. In all clusters GIRAFFE will be used to target faint cluster members (down to V = 19), while parallel UVES fibres will be fed with brighter or key objects (down to V = 16.5), to be used for accurate multi-element abundances.

For the field survey, two GIRAFFE high resolution setups are used, HR10 and HR21, which include a large enough number of Fe I and Fe II lines for astrophysical parameter determination, along with lines of other key elements. The parallel UVES observations will use the 580 nm setup. For the clusters, and depending on the specific targets, six GIRAFFE setups are employed (HR03/05A/06/14A/15N/21). HR03/05A/06/14A contain a large number of spectral features, to be used to derive radial velocities and astrophysical parameters of early-type stars. HR15N/21 are instead the most appropriate gratings for late-type stars; they access a large enough number of lines to derive radial velocities, as well as to retrieve key information on the star's characteristics (e.g., temperature, [Li/H], accretion rates, chromospheric activity, rotation). For UVES, the 520 nm and 580 nm setups will be used for hot and cool stars, respectively.

Gaia-ESO Survey methodology and implementation activities

The Gaia-ESO Survey is a very large project, with substantial resource commitments in terms of telescope access. The greatest cost, and opportunity, is of course the time of the 300 scientists dedicated to this project over the next five years. To guarantee that this resource is utilised with maximal efficiency and effectiveness, we have developed a very detailed plan, clarifying every stage of information flow, decision dependency, data processing, information storage, and provision of documented data for team scientific analysis. This involved a 42-page science case, supplemented by a 25-page management plan, describing every stage of the project implementation, from science goal through detailed target selection, data processing, and readiness for scientific analysis. The science plan was reviewed and approved by a special ESO-organised science strategy panel, and by the ESO Time Allocation system. The management plan was reviewed by ESO and agreed after minor iteration. These documents form a memorandum of understanding between ESO

Figure 4. GIRAFFE spectra of a Milky Way star in the outer thick Disc (grating setting HR21, upper panel) and a member of the young cluster γ Velorum (setting HR15N, lower panel). Note the strong Hα emission and lithium 6708 Å line in the latter, both indicators of youth.

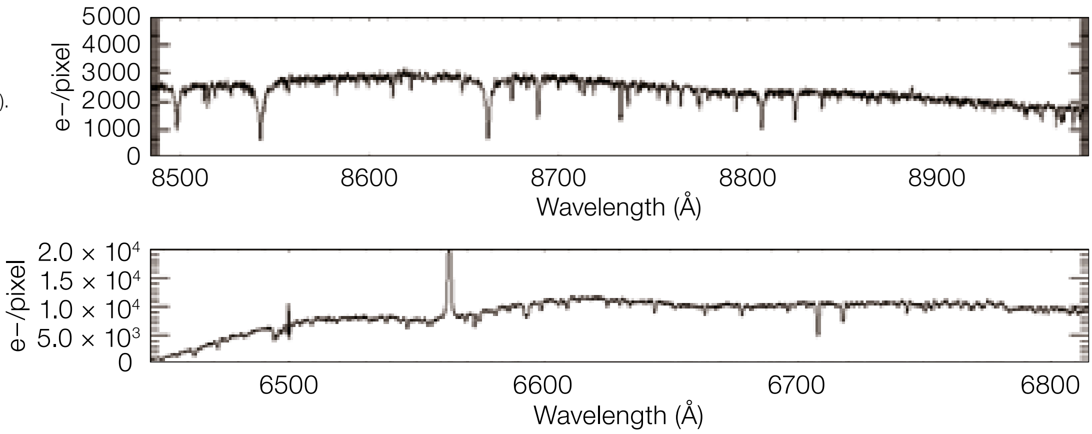
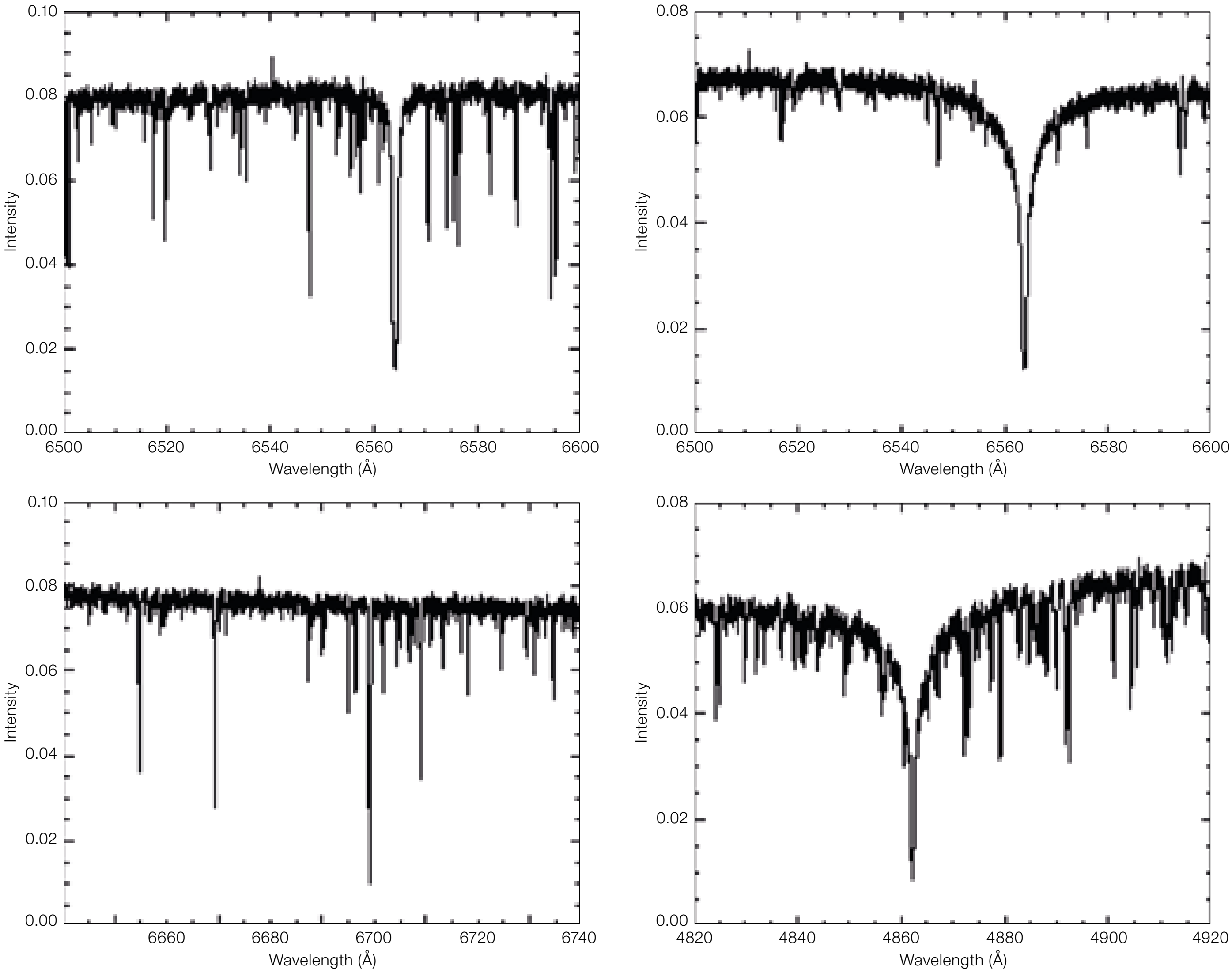


Figure 5. Left panel: UVES spectra are shown of a member of γ Velorum around Hα (upper) and the lithium line (bottom). Right panel: UVES spectra of a Milky Way field star in the Hα (upper) and Hβ (lower) spectral regions.



and the Co-PIs on Survey delivery. They are available on the survey wiki[1] and (forthcoming) web page[2].

A Survey Consortium Working Group structure has been created to match the information and requirements flow, from the scientific context which defines source selection, through selection, observation, data reduction, classification, spectrum analysis, astrophysical parameter determination, and collation of all the information necessary for science verification analysis (see Figure 3). The survey activities are structured into 18 Working Groups, one for each level of critical specialist activity, each with an identified coordinator, remit, requirements, and deliverables.

A 19th Working Group dedicated to communications is also included. The Working Group coordinators report to the Co-PIs, who are advised by a Steering Group, which acts as the project management board. The Steering Group members act to assist the Co-PIs in supporting the consortium activities. The Steering Committee and Working Group leads are identified as co-authors of this article. There are many more workers than there are managers — which is why the survey works!

At the heart of the survey data processing are the spectrum analyses. All extracted spectra are processed through general purpose pipelines, to refine astrophysical parameters, and deliver elemental abundances to a level appropriate for the relevant stellar type and available S/N. Separate pipelines manage, respectively, hot, warm and cool stars, as well as pre-main sequence stars, and GIRAFFE and UVES spectra. It is a strength of this Gaia-ESO Survey team that it includes a majority of Europe's spectrum analysis groups, which between them have available a wealth of expertise. All groups have agreed to adopt a fixed set of atomic data and model atmospheres for the analysis of FGK stars. Very considerable coordination between the teams has been underway for some months. This range of analysis excellence will be applied to the various stellar and data types as appropriate. Sanity checking will then deliver, for each star target, a "best" set of parameters and abundances, with corresponding random and systematic errors, and an explicit analysis of the effect of alternative analysis assumptions. All these results will be archived for later analysis, both in the operational database, and the Survey archive for later public analysis. All survey products will be delivered to the ESO archive.

Complementary activities

Given the outstanding range of science opportunities in near-field cosmology, it is not surprising that Galactic surveys are a major research activity globally. One of these, AEGIS, using the Australian AAO 2dF facility, is coordinated with the Milky Way field part of Gaia-ESO, with shared photometric targets, and closely coordinated follow-up science planning. AEGIS, which targets candidate Halo stars identified from the SkyMapper photometric survey, aims to observe the rare relatively bright metal-poor stars, to add statistical weight in the wings of the Gaia-ESO distribution function. The AEGIS PI is Stefan Keller at the Australian National University (ANU). A second complementary survey is the RAdial Velocity Experiment (RAVE)[3]: a very-large-number survey, albeit restricted to low resolution calcium triplet spectra, and limited to stars brighter I = 13 mag, brighter than the Gaia-ESO bright limit. RAVE kinematics are good, and so complementary analyses of the joint RAVE and Gaia-ESO kinematic samples will be enormously powerful. The RAVE PI is Matthias Steinmetz at AIP Potsdam. In order to maximise synergy between archive spectroscopy, the various bright star surveys underway, such as RAVE, or planned, Gaia-ESO, and Gaia itself, are investing considerable effort establishing common abundance calibrations between available and planned datasets. This work, coordinated by Elena Pancino and Sofia Feltzing, should ensure a real long-term legacy from the Gaia-ESO Survey.

First light!

The first observations were obtained on 31 December 2011, by Thomas Bensby and Christophe Martayan. While the first spectrum was, unsurprisingly, a twilight standard star, real survey data soon followed. During the first run 12 different fields in the 10 Myr cluster γ Velorum were observed, along with three fields in the outer thick Disc. Examples of GIRAFFE and UVES spectra are shown in Figures 4 and 5.

Prospects

The big themes in European astronomy require both space and ground-based observations.

In the field of Milky Way studies, the key recommendations of the joint ESA–ESO working group (chaired by Catherine Turon) can be summarised in two words covering both space and ground: "Gaia" and "spectroscopy". The planned spectroscopic data products from the Gaia-ESO Survey will all be available to the community roughly at the same time as the first intermediate Gaia catalogue, expected around 2016. Future dedicated survey spectroscopy facilities are under study to allow Europe to carry the torch forward in years to come, learning from this first effort. The European scientific community has an enormous opportunity to address a multitude of Galactic astronomy topics with combined spectroscopic and Gaia data.

Acknowledgements

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Links

[1] Gaia-ESO Survey wiki page: http://great.ast.cam.ac.uk/GESwiki/GESHome
[2] Gaia-ESO Survey web page: http://www.gaia-eso.eu
[3] RAVE web page: http://www.rave-survey.org
[4] Homepage of ESF GREAT: http://www.great-esf.eu

Teenage Galaxies

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The early growth stages of galaxies are still poorly understood. The aim of the MASSIV survey is to better understand the key processes that govern the evolution of galaxies at redshifts $z \sim 1$–2, a particularly turbulent period similar to the teenage years. This paper presents this ambitious survey, together with the main results obtained so far from this ESO Large Programme with SINFONI at the VLT.

The details of the evolution processes that drive galaxy assembly are still largely unconstrained. During the last decade, major spectroscopic and multi-wavelength photometric surveys explored the high-redshift Universe in depth, enabling us to follow the evolution of large numbers of galaxies over cosmological timescales. Even if these data enabled significant progress concerning the knowledge of the global properties of different galaxy populations in different environments, more detailed constraints are needed to understand the main physical processes involved in the formation and evolution of galaxies. Based on observational and/or theoretical arguments, we know that galaxy merging is at work in the growth of galaxies. Cold gas accretion along cosmic filaments has also been emphasised as an efficient process for sustaining high star formation rates and explaining the clumpy nature of high-redshift galaxy discs. However, observational signatures for cold accretion are still being debated, and we do not know yet the cosmic epoch during which either one of these two processes (mergers and cold accretion) was dominant.

Spatially-resolved observations of high-redshift galaxies have begun to give some clues that help to answer this question, as they allow us to probe both the internal properties (kinematics, distribution of metals, etc.) and close environment of distant galaxies. However, most of the previous surveys have concentrated their efforts on the $z > 2$ Universe (e.g., SINS; Förster Schreiber et al., 2009; 2011) or on lower redshifts $z < 0.8$ (IMAGES; Puech et al., 2008). Much less is known of the $z \sim 1$–2 redshift range, which corresponds to a lookback time of 8 to 10 billion years. However, we know that at the peak of cosmic star formation activity galaxies experience major transformations. Is cold gas accretion still an efficient process for assembling galaxies or are major mergers predominant, as seems to be the case at later epochs?

MASSIV (Mass Assembly Survey with SINFONI in VVDS) tackles this issue by surveying a representative sample of star-forming galaxies in the redshift range $z \sim 1$–2 (Contini et al., 2012). With the detailed information provided by SINFONI on individual galaxies, the key science goals of the MASSIV survey are to investigate: (1) the nature of the dynamical support (rotation *vs*. dispersion) of high-z galaxies; (2) the respective role of mergers (minor and/or major) and gas accretion in galaxy growth; and (3) the process of gas exchange (inflows/outflows) with the intergalactic medium through the derivation of metallicity gradients.

A representative sample of high-z galaxies

The MASSIV sample includes 84 star-forming galaxies drawn from the VIMOS VLT Deep Survey (VVDS; Le Fèvre et al., 2005) in the redshift range $0.9 < z < 2.2$. The main advantage of selecting galaxies from the VVDS is that it is a complete magnitude-selected survey avoiding the biases linked to *a priori* colour selection techniques. This unique sample of more than 4400 galaxies, with accurate and secure spectroscopic redshifts between 0.9 and 2, contains both star-forming and passive galaxies distributed over a wide range of stellar masses and star formation rates. It enabled us to easily define volume-limited subsamples of high-z galaxies for integral field spectroscopic follow-up.

Three selection criteria were applied to selected MASSIV targets inside the VVDS. First, galaxies were selected to be star-forming, in order to ensure that the brightest rest-frame optical emission lines (mainly Hα and [N II] 6584 Å, or in a few cases [O III] 5007 Å) used to probe kinematics and metallicity are observed with SINFONI in the near-infrared *J*- or *H*-bands. The selection of star-forming galaxies up to redshift $z \sim 1.5$ (75 % of MASSIV galaxies) was based on the strength and equivalent width of the [O II] 3727 Å, emission line measured on VIMOS spectra (see Figure 1). Galaxies at higher redshift (21 objects with $z > 1.5$) were selected to be star-forming on the basis of their restframe ultraviolet continuum and/or absorption lines.

We further restricted the sample by taking into account two important observational constraints. The expected emission line to be observed with SINFONI (mainly Hα) had to fall far away from the numerous bright OH night-sky lines, restricting considerably the observable redshift domain. Moreover, 90 % of MASSIV galaxies were selected to be further observable at higher spatial resolution with the adaptive optics system of SINFONI or with future imaging/spectroscopic facilities. In these cases, a bright star close enough to the target is needed

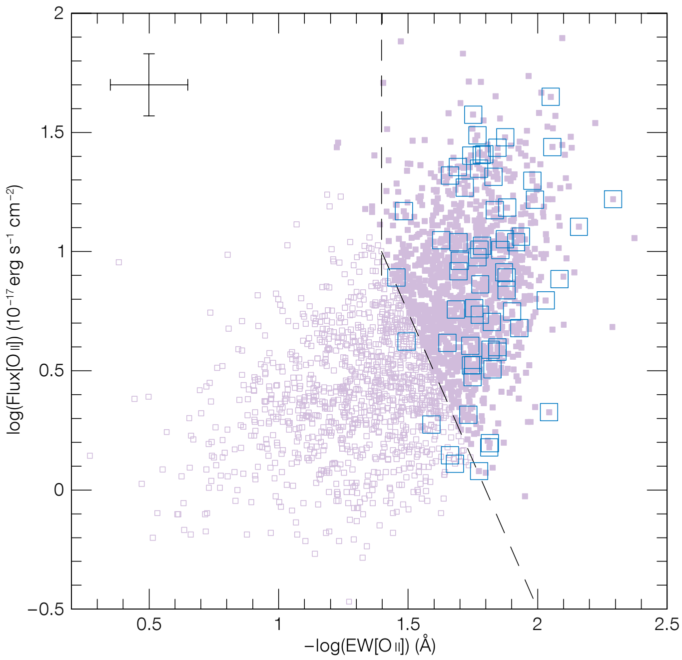


Figure 1. Selection of MASSIV star-forming galaxies in the VVDS sample (small grey symbols). The dashed line indicates the selection box based on [O II] 3727 Å, emission-line equivalent width, used as a proxy for star formation. The 63 galaxies in the redshift range $z \sim 0.9$–1.5 selected for SINFONI observations are indicated by large blue squares.

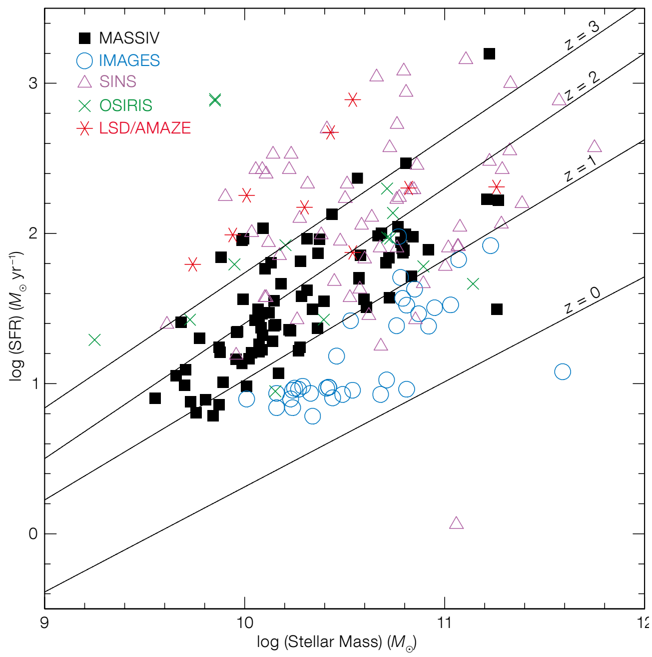


Figure 2. Relation between star formation rate and stellar mass for high-z galaxies is shown. The MASSIV sample (black filled squares) is compared with other major integral field spectroscopic surveys of distant galaxies: IMAGES ($z \sim 0.4$–0.75, blue circles), SINS ($z \sim 1.4$–2.6, magenta triangles), OSIRIS ($z \sim 1.5$–3.3, green crosses), and LSD/AMAZE ($z \sim 2.6$–3.8, red asterisks). The black lines represent the empirical relations between star formation rate and stellar mass for different redshifts between $z = 0$ and $z = 3$ (Bouché et al., 2010).

for the zero order tip-tilt corrections. All in all, starting from a parent sample of more than 4400 VVDS galaxies at $z = 0.9$–2.0, only ~ 10 % (~ 540 galaxies) satisfy the above-mentioned criteria. The 84 galaxies defining the MASSIV sample were selected randomly from these targets.

The main advantage of MASSIV, compared to other high-z integral field spectroscopic surveys, is its representativeness for galaxies with star formation rates as low as 5 $M_\odot$/yr. In contrast, surveys like SINS (e.g., Förster Schreiber et al., 2009), OSIRIS (e.g., Law et al., 2007) and LSD/AMAZE (e.g., Gnerucci et al., 2011; Mailoino et al., 2010) target galaxies selected in various, and hence heterogeneous, colour-selected samples (Lyman-break galaxies, BzK, etc.). These surveys mainly probe galaxies at a relatively higher star formation level for a given stellar mass (as shown by the comparison in Figure 2). With a selection based mainly on the [O II] 3727 Å, emission line, MASSIV is essentially a flux-limited sample which provides a fair representation of galaxies in the stellar mass regime 10^9–10^{11} $M_\odot$ down to a relatively low star formation level (Contini et al., 2012).

The integral field spectroscopic observations of the MASSIV sample were performed with SINFONI mounted at the Cassegrain focus of the Very Large Telescope (VLT) Unit Telescope 4. Most of the data (90 %) were collected in service mode during several observing periods between April 2007 and January 2011, as part of the ESO Large Programme 179-A.0823. However, 11 galaxies of the MASSIV sample (including three with duplicated observations) were observed during two pilot runs with SINFONI in September 2005 and November 2006 (performed in visitor mode).

To map the Hα, [N II] 6584 Å, and [S II] 6717,6731 Å, emission lines, or [O III] 5007 Å, and Hβ for four galaxies of the MASSIV sample, we used the J or H gratings, depending on the redshift of the sources. The vast majority of the observations (74 galaxies) were carried out in seeing-limited mode with the largest pixel scale of 0.125 arcseconds/pixel, giving a field of view (FoV) of 8 by 8 arcseconds. However, we were able to observe 11 galaxies at higher spatial resolution with adaptive optics. For seven of these, we selected the intermediate 0.05 arcsecond/pixel scale with FoV of 3.2 by 3.2 arcseconds to take full advantage of the gain in angular resolution provided by the adaptive optics. For the four other targets, we used the larger pixel scale as a trade-off between enhanced angular resolution and sensitivity (see Contini et al. [2012] for a detailed discussion). The observing conditions were generally good, with clear-to-photometric sky transparency and typical seeing of 0.5–0.8 arcseconds at near-infrared wavelengths. The total on-source integration times ranged on average from 80 to 120 minutes.

The first results of the MASSIV survey, recently published in Epinat et al. (2012), Queyrel et al. (2012), and Vergani et al. (2012), are based on the first epoch sample. It contains 49 galaxies in the redshift range $0.9 < z < 1.6$ that were observed before January 2010. The fully calibrated datacubes and derived properties of this sample are already publicly available through the MASSIV database[1].

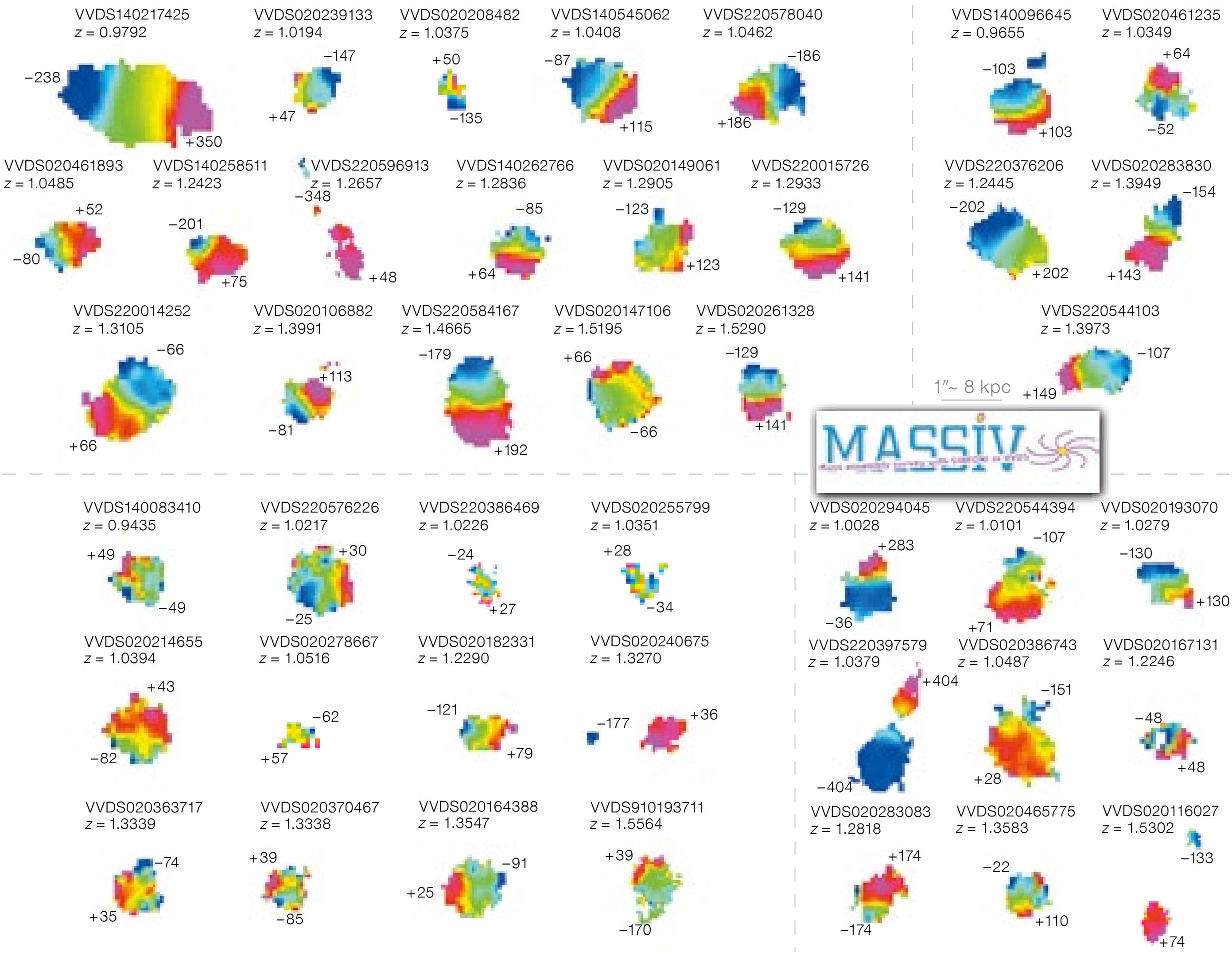
Mergers and discs at $z \sim 1.2$

The ionised gas kinematics of MASSIV galaxies was studied through the brightest emission line available in the SINFONI spectra: mainly Hα, or [O III] 5007 Å in a few cases. Among the various dynamical states of galaxies, the easiest to probe is the rotating disc. We have thus tested for the presence of a rotating disc in each MASSIV galaxy and then recovered the fundamental dynamical parameters within this hypothesis (Epinat et al., 2012). However, some parameters, such as the rotation velocity, are difficult to constrain from the kinematic modelling alone. In order to reduce the number of free parameters, we first estimated the centre and the inclination of the galaxies from their morphology as measured on the Canada France Hawaii Telescope (CFHT) Legacy Survey *I*-band images, making the assumption that the stars and the ionised gas follow a common distribution.

Using this information, 46 MASSIV galaxies have been classified into four broad classes (see Figure 3), based on their kinematics (rotating discs or not) and close environment (isolated galaxies *vs.* interacting/merging systems).

The fraction of interacting/merging systems in the MASSIV sample is at least ~ 30 % (Epinat et al., 2012). At first glance, this fraction looks comparable to that found at $z \sim 2$ in the SINS sample. However, SINS mergers are identified mainly using kinemetry, a technique based on the degree of perturbation observed in the velocity fields, whereas the identification of interacting systems in MASSIV is based essentially on the detection of several star-forming components inside ongoing mergers or of companions around the main galaxy. The proportion of mergers in MASSIV is thus a lower limit, as it could well be that a significant number of apparently isolated non-rotating

Figure 3. Velocity fields for 42 star-forming galaxies at $z \sim 0.9$–1.6 observed with SINFONI as part of the MASSIV survey. Blue to red colours correspond to regions of the galaxies that are approaching and receding relative to their systemic velocity. All galaxies are shown on the same angular scale indicated by the horizontal bar (1 arcsecond ~ 8 kiloparsecs at $z \sim 1$–2). Galaxies are classified into four broad classes based on their kinematics (top: rotating discs, bottom: non-rotating objects) and close environment (left: isolated galaxies, right: interacting/merging systems), demarcated by dashed lines.



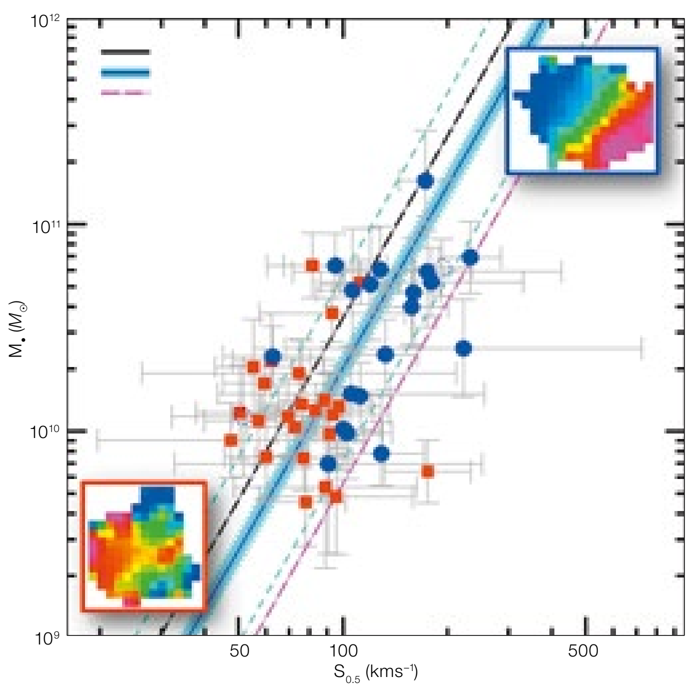


Figure 4. Relation between stellar mass and velocity (rotation + dispersion) of MASSIV galaxies. Blue points indicate rotating discs whereas red squares are for non-rotating galaxies. Examples of SINFONI velocity fields for these two kinematic classes are shown in insets. The relation obtained with MASSIV at $z \sim 1.2$ (highlighted blue line) is compared with those derived at $z \sim 1$ (black line; Kassin et al., 2007) and $z \sim 3$ (magenta line; Gnerucci et al., 2011).

galaxies are in fact ongoing mergers or merger remnants. A dedicated analysis of the merger rate from the observed pairs at $z \sim 1$–2 is underway and makes use of the entire MASSIV sample (López-Sanjuan et al., in prep.).

Rotating discs represent ~ 50 % of the MASSIV first epoch sample (Epinat et al., 2012). These galaxies are on average more massive, more star-forming and larger than non-rotating ones (Vergani et al., 2012), but with similar velocity dispersion (~ 60 km/s). An evolution in the fraction of rotating discs is clearly seen over the last 10 Gyr of the Universe. The fraction of rotating systems indeed increases continuously from $z \sim 3$ (~ 35 %, Gnerucci et al., 2011) to $z \sim 0.6$ (~ 65 %; Puech et al., 2008), supporting the scenario in which gas in star-forming systems is stabilising into discs as the Universe evolves.

It appears clearly that the non-rotating systems (~ 30 % of the MASSIV sample; Epinat et al., 2012) are galaxies with a low observed velocity shear (< 50 km/s) or galaxies for which the kinematics indicate some ongoing interactions. Such a population of galaxies has already been observed at higher redshift both in the SINS and LSD/AMAZE samples. These objects are smaller on average than rotators and are often associated with interacting systems. However, the exact nature of these non-rotating objects (spheroids, face-on discs, or merger remnants) is still unclear. Higher spatial resolution imaging and integral field spectroscopy is clearly needed to solve this issue.

The evolution with cosmic time of fundamental scaling relations, connecting for example mass and dynamics of galaxies (the well-known Tully–Fisher relation), is still a matter of debate and controversy. The discordant results obtained so far might be due to differences in sample selection and/or observing limitations, but there is another quantity which could play a significant role: the gas turbulence.

Indeed, the median value of velocity dispersion measured in MASSIV galaxies (~ 60 km/s) marks a transition between turbulent discs (~ 80–100 km/s) seen at higher redshift ($z \sim 2$–3) and more "stable" discs (~ 20–40 km/s) observed in the nearby Universe. This transition of the gaseous velocity dispersion is partly responsible for the increase of the rotational support when galaxies evolve. Taking into account the ordered (rotation) and chaotic (dispersion) motions, there is a clear relation between stellar mass and dynamics of MASSIV galaxies (see Figure 4), a relation which evolved significantly between $z \sim 3$ and $z \sim 1$ (Vergani et al., 2012). At high redshift, we think that mass assembly driven by cold flows is responsible for the high level of turbulence in the gaseous discs. In this framework, results from the MASSIV survey suggest that at $z \sim 1.2$ cold gas accretion is less efficient than at higher redshift.

A surprising distribution of metals

Unveiling the chemical enrichment of galaxies at various epochs is a key issue to constrain their star formation history and their interplay with the surrounding intergalactic medium. In particular, the way metals are distributed inside galaxies gives valuable information about the gas exchange processes (accretion and ejection) between galaxies and their close environment. Until recently, only global measurements of galaxy metallicity were available in the high-z Universe. The high sensitivity of SINFONI enabled resolved metallicity distributions in high-z galaxies to be achieved and was one of the major objectives of our survey.

This goal has been achieved so far for 26 MASSIV galaxies, where we have measured the flux ratio between [N II] 6584 Å, and Hα emission lines (used as a proxy for metallicity) in concentric regions (Queyrel et al., 2012). These regions are centred on the Hα peak emission in each galaxy, which most often corresponds to the kinematical centre of the galaxy. The sizes of the annular regions were adjusted so as to have enough signal for a reliable measurement of the faint [N II] 6584 Å line. This allowed us to quantify the radial profile of the [N II]/Hα line ratio and hence to derive the metallicity from the inner to the outer parts of each galaxy. The metallicity gradients of the 26 MASSIV galaxies are shown in Figure 5.

The most surprising result is the discovery of seven galaxies with a positive metallicity gradient (Queyrel et al., 2012), where the metal content increases from the centre to the outer parts of the galaxy. This result is surprising because this behaviour is rarely observed in nearby galaxies. A close inspection of these galaxies reveals that the majority of them (5/7) are interacting or merging systems. This indicates that interactions might be

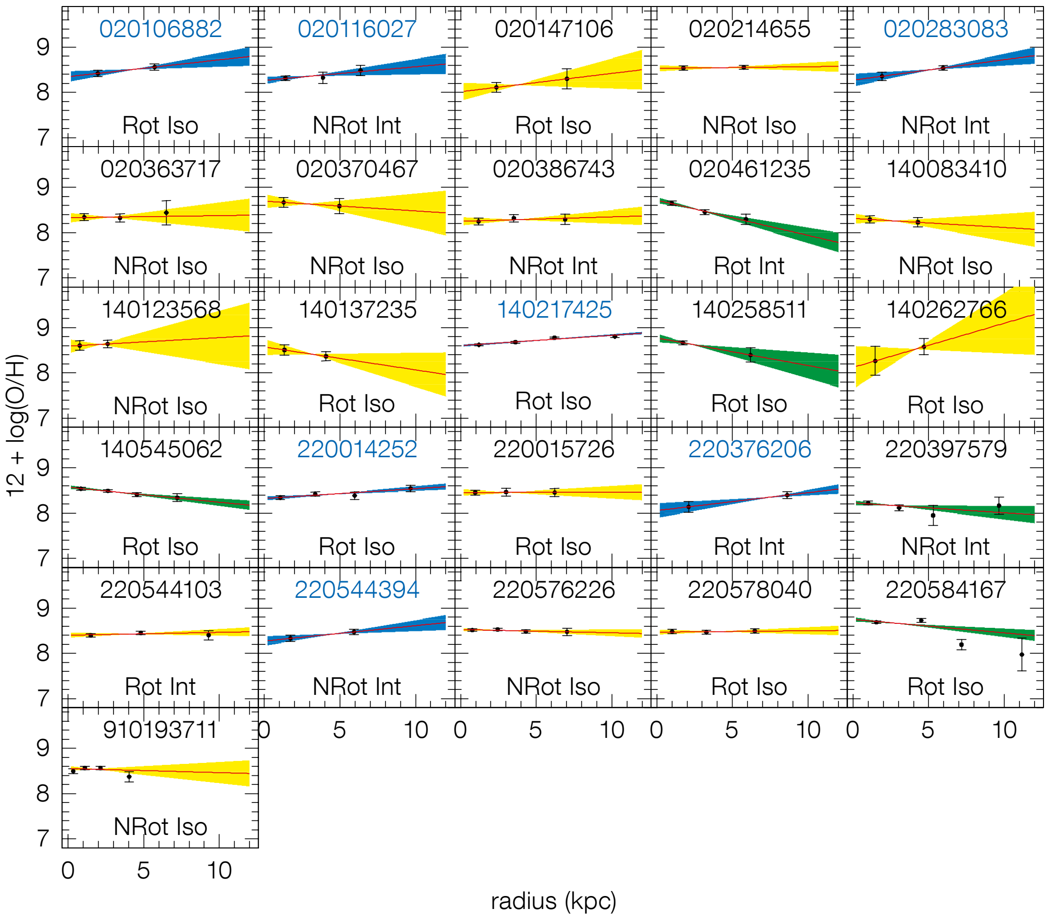


Figure 5. Metallicity gradients for 26 MASSIV galaxies. The yellow/blue/green regions represent the 1σ errors associated to the gradients (red lines). Blue (green) labels indicate the galaxies for which the gradient is positive (negative) with a high confidence level. For each galaxy the dynamical (Rot = rotating disc, NRot = no rotation) and environment (Iso = isolated, Int = interacting) classes are indicated.

the main mechanism responsible for a significant infall of metal-poor gas onto the galaxy centre.

The other mechanism put forward to explain the high occurrence of positive metallicity gradients in $z \sim 3$ isolated discs is cold accretion (Cresci et al., 2010). However this occurrence drops to about 15–20 % at $z \sim 1.2$ (Queyrel et al., 2012) and is almost equal to zero in the local Universe. If cold accretion is the main process able to explain the positive metallicity gradient in high-z isolated discs, this mechanism does not dominate the galaxy assembly at lower redshifts ($z < 2$).

To conclude, all the results obtained so far from the MASSIV survey favour a scenario in which the mass assembly of star-forming galaxies is progressively shifting from a predominance of smooth cold gas accretion to a predominance of merging as cosmic time evolves, with a transition epoch around $z \sim 1$–1.5.

Next steps

The SINFONI observations are now completed. The full exploitation of the unique MASSIV dataset is underway, looking forward to further new and exciting discoveries. In the short term, doubling the statistics in the highest redshift range ($z > 1.2$) will allow us to better probe the dominant mechanisms at play in the overall process of galaxy assembly. New observations of MASSIV galaxies at the VLT with X-shooter and SINFONI are already planned to address specific questions, such as the ubiquity of positive metallicity gradients and the level of gas turbulence in high-z discs. In the longer term, taking the census of the cold gas content and dynamics in MASSIV galaxies with the Atacama Large Millimeter/submillimeter Array (ALMA) will be the obvious step towards a full description of the galaxy growth in the young Universe.

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Vergani, D. et al. 2012, A&A, in press, arXiv:1202.3107

Links

[1] MASSIV database: http://cosmosdb.lambrate.inaf.it/VVDS-SINFONI/

Upper: Prince Philippe, Crown Prince of Belgium (standing third from right) visited Paranal on Monday 5 December 2011 and is shown accompanied by members of the Belgian delegation and ESO representatives Massimo Tarenghi (third from left) and Michael Sterzik (first from left). See Release eso1149 for more details.

Lower: As part of a visit during the ESO Fellows Days, Fellows and students had the opportunity to explore the unusual ice and snow formations called *penitentes*, which form because snow sublimates rather than melts at ALMA's high altitude. See West and Emsellem, p. 44.

Report on the Workshop

Ten Years of VLTI: From First Fringes to Core Science

held at ESO Headquarters, Garching, Germany, 24–27 October 2011

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[2] ESO

The tenth anniversary of first fringes with the VLT interferometer (VLTI) was celebrated by a workshop to trace the history and progress of VLTI, review the science achievements and present the next generation instruments. Highlights of the meeting are reported and the panel discussions summarised.

To celebrate the tenth anniversary of the first fringes at the Very Large Telescope Interferometer, more than 100 astronomers from diverse scientific backgrounds came together at ESO's Headquarters. The four-day meeting featured 54 talks, of which ten were invited reviews; there were also 26 poster presentations and two panel discussions. The presentations are available for download from the conference web page[1].

The stage was set by an account of how the VLTI came into being, from the first suggestion by Antoine Labeyrie to the political birth of the VLTI in the late 1970s, to ESO Council approval in 1987 and the financial and technical challenges that had to be surmounted after the approval. A good place to read up on the genesis of the VLT and VLTI is Woltjer (2006).

Science sessions

The scientific programme consisted of three days of talks and half a day of plenary discussions. The scientific talks were divided into sessions reflecting the diversity of the research areas in which optical interferometric observations play a role: star and planet formation, stellar astrophysics, evolved stars, asteroids and active galactic nuclei (AGN). Here we summarise a number of results that underline the impact of optical interferometry, and especially of the VLTI, on these areas.

Figure 1. The conference photo in the entrance hall of ESO Headquarters.

The field of star and planet formation was introduced by three review talks. During the formation of stars, an accretion disc of gas and dust forms through which material is transported close to the young star. This "protoplanetary disc" is also thought to be the place of planet formation, as it provides the dust particles that are built up into ever larger grains and agglomerations until eventually a planet emerges. Despite its importance in star and planet formation, the detailed structure of the innermost regions of these discs (the terrestrial-planet-forming region) was unknown before the advent of infrared interferometry, due to the lack of resolution of single-dish telescopes. Studies with the VLTI and other interferometers have resolved the inner rims of these discs and confirmed that they lie close to the dust sublimation radius. They have also probed the geometry of the disc and found that these discs have a "puffed up" inner rim and that the rim is curved, as theoretically expected.

A number of talks reported on several recent attempts to reconstruct images of protoplanetary discs using VLTI data. Furthermore, the dust composition of the discs was examined and a crystallinity gradient found, in the sense that there is a larger crystallinity in the inner parts of the disc, as expected from thermal reprocessing of dust grains in the vicinity of the sublimation radius. Towards the end of the session, the first results from an interferometric survey of T Tauri stars that is currently being conducted with the VLTI visitor instrument PIONIER (see Zins et al., 2011) were presented. For the stars studied so far, the total flux was lower than expected from an extrapolation of the visibility model, indicating contributions from larger scales (possibly through scattering) around these stars.

In the field of stellar astrophysics, the review talks emphasised that the mass–radius relation is essential for stellar models and pointed out how observations with optical interferometers constrain such models by directly measuring the radii of stars. Recent observations actually found the radii to be slightly

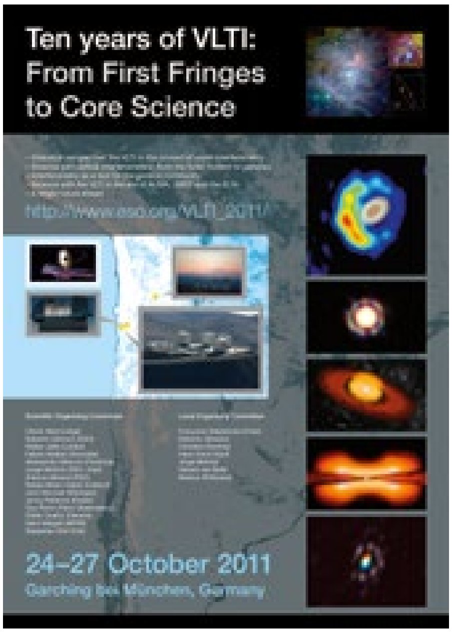

Figure 2. Conference poster depicting the VLTI among the future facilities in the next decade — ALMA, E-ELT and the James Webb Space Telescope (JWST) — and a selection of images of a variety of circumstellar discs.

larger than predicted by models — a result which modellers will have to address. Talks on the cosmological distance scale highlighted the importance of well-understood errors in Cepheid distance measurements to calibrate the first rung of the cosmic distance ladder. A programme to reach beyond the current uncertainty of the present-day Hubble parameter H_0 (3 %) by studying Galactic Cepheid stars with the interferometric Baade–Wesselink method was presented. In this method the diameter and pulsation velocity of the stars are measured interferometrically and spectroscopically to achieve a distance measurement independent of the period–luminosity relation. Using the FLUOR instrument at the US-based Center for High Angular Resolution Astronomy (CHARA) interferometer, it was found that the assumptions about the pulsation of the stars break down when a precision of better than 1.5 % is reached. In order to increase the precision, more refined stellar models are therefore needed.

For the evolved stars, the review talk stressed the many aspects in which interferometric observations contribute. For example, by following the time evolution of the outburst of the recurrent nova T Pyxis earlier in 2011 with both the VLTI and the CHARA Array, it was shown that simple spherical models for the outflowing material are incorrect, and that the morphology is best described as a bipolar flow — this was later confirmed by NACO observations.

The asteroid observations with the VLTI finally convinced us that interferometry might contribute to saving the planet! With MIDI observations it is possible to measure the size, shape and thermal inertia of the main belt asteroids — quantities that are otherwise hard to quantify. The thermal inertia determines the strength of the Yarkovsky effect that can modify the orbits of the asteroids so that they may become potentially dangerous near-Earth objects.

For the area of AGN research, the review talks concentrated on the progress brought about by current interferometers and outlined the expectations for future interferometers. Apart from confirming the unified model of AGN, which invokes a dusty "torus" to explain the two different spectral types, observations with the VLTI also showed that the tori of edge-on (type 2) objects differ from galaxy to galaxy, both in geometry and in temperature structure. On the other hand, face-on (type 1) objects seem to show a uniform radial brightness distribution, as shown in a mini-survey using both near-infrared observation at the Keck Interferometer and MIDI at the VLTI. A debate is still open as to whether or not the sizes of the tori scale uniformly with AGN luminosity (i.e., are independent of spectroscopic type) and whether or not this relation holds also for high luminosities. The first VLTI Large Programme is addressing that question. The first AMBER observations of an AGN in "no track mode" using the AMBER instrument (see Malbet et al., 2007) were also presented. In order to spectro-interferometrically resolve an emission line in the broad line region using the differential phase signal, a factor of about five in sensitivity improvement is still needed.

Next generation instrumentation

The science talks were followed by a session presenting the next generation instruments of the VLTI. A report on the first science results from PIONIER demonstrated how efficient interferometric observations are, once four telescopes are combined at the same time. The latest results of the astrometric commissioning of the PRIMA instrument (see van Belle et al., 2008) were presented.

The near-infrared second generation VLTI instrument GRAVITY was presented, with particular emphasis on the technological challenges (see Eisenhauer et al., 2011). In order to achieve the necessary resolution to observe orbits and flare events at less than six Schwarzschild radii from the supermassive black hole in the Galactic Centre — this corresponds to an angle of 10 microarcseconds — the GRAVITY team will improve the infrastructure of the VLTI (including infrared adaptive optics for all telescopes, the metrology system from the instrument to the VLT primary mirror, and a sophisticated fringe tracker using a Kalman controller) as well as provide a very sensitive instrument by harvesting as many photons as possible.

The thermal infrared second generation VLTI instrument MATISSE was also presented. Compared to the current mid-infrared instrument, MIDI (Leinert et al., 2003), MATISSE will widen the spectral coverage to include the *L*-band, which contains several interesting spectral features of water ice and polycyclic aromatic hydrocarbons (PAHs). Like GRAVITY, it will also combine the light of four telescopes, providing six baselines and three independent closure phases at a time and thereby allow the reconstruction of real images for the first time in the *L*- and *N*-bands at angular resolutions of about 3–10 milliarcseconds.

Synergies

The two largest ESO projects of the decade, the Atacama Large Millimeter/submillimeter Array (ALMA) and the European Extremely Large Telescope (E-ELT), were presented, and in particular how they are expected to work together with the

VLTI. Crucially, ALMA is offered as a high-fidelity imager — and not as an interferometer — to open it up to the whole science community and not only to those who are interferometrically inclined. At the end of the session views were presented on the high-resolution astronomy infrastructure a few years into the future. In contrast to ALMA's approach, the audience was asked to change its mental picture of optical interferometers: these are not high-resolution facilities for all kinds of science, but very specialised observatories that contribute crucially to a few selected science cases.

Panel discussions

On the last day of the workshop there were two panel discussions: the future of the VLTI; and the challenges of (optical) interferometers as a common user facility. The former was considered as an initial discussion forum to assemble the thoughts of the community and provide ideas for the further development of the VLTI after the second generation instruments. This discussion provides invaluable input to help ESO shape its plans for the future of the VLT/I in the E-ELT era.

The panel moderator gave an overview of recent developments that appear interesting for the future of the VLTI. One of the most promising developments is the "hybrid mode", i.e. the combination of one (or more) of the large Unit Telescopes (UTs) with one (or more) of the smaller Auxiliary Telecopes (ATs). This mode was first demonstrated in 2011 and will offer more baselines and better sensitivity (compared to AT-only operations), answering two of the biggest wishes of VLTI users. Another important development is the introduction of the infrared avalanche photodiode detectors that are on the verge of entering astronomy. It is believed that these photon-counting detectors will change interferometric observation and bring about a breakthrough in terms of sensitivity and the way interferometers can be operated.

Regarding the further development of the VLTI, several participants suggested exploring the possibility of expanding the spectral coverage to the visual. This would require a re-coating of all mirrors in the VLTI optical path, but since the maximum VLTI baseline length is limited by the size of the Paranal platform, this is the only way to increase the resolution, which is seen as the necessary step forward for stellar interferometry. While the visual waveband would also be interesting for AGN, more sensitivity and reliability for observations of weak targets are of greater interest to AGN interferometrists. Hybrid UT–AT combinations would add new baselines to the array and thereby improve image fidelity and they would also increase the sensitivity compared to AT-only baselines. The prevailing outlook at the panel discussion on the VLTI as a common user facility was that the ability to reconstruct real images will bring a huge step forward and attract new users to the VLTI.

Acknowledgements

The authors would like to thank Hendrik Linz, Henrik Beuther and Myriam Benisty for input and comments.

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Links

[1] Workshop webpage: http://www.eso.org/sci/meetings/2011/VLTI_2011.html

A photograph from 2009 showing the Very Large Telescope Interferometer (VLTI) laboratory at the Paranal Observatory. In the foreground, undergoing maintenance, the differential delay lines of the PRIMA (Phase Referenced Imaging and Microarcsecond Astrometry) instrument are seen.

ESO Telescope Bibliography: New Public Interface

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Silvia Meakins[1]

[1] ESO

The ESO Telescope Bibliography (telbib) is a database of refereed papers published by the ESO users' community. All papers that use, partly or exclusively, data from ESO telescopes are included. The front end of telbib has undergone a complete transformation and a state-of-the-art interface has been implemented to provide new features and sophisticated search functionality. telbib has been created and will be further developed by the ESO librarians.

Introduction

The ESO library maintains the Telescope Bibliography[1], a database of refereed papers that use ESO data. It is compiled by scanning the major astronomy journals for scientific papers that contain any of the ESO-defined keywords (e.g., telescope and instrument names). Bibliographic information, citations and some further metadata are imported from the NASA Astrophysics Data System (ADS)[2]. Standardised descriptions of telescopes and instruments, survey names and other tags as well as programme IDs are assigned by the ESO librarians.

Access to the full texts of papers in telbib is governed by subscription. telbib records contain links to the ADS from where typically the PDF and HTML versions can be obtained, provided a subscription for these journals is in place. Alternatively, the articles may be available through open access agreements. In many cases ADS also provides links to the freely available manuscripts at the arXiv/astro-ph e-print server.

telbib contains records from 1996 onwards. Programme IDs and instrument tags are available for all papers using Paranal or Chajnantor data as well as for papers based on La Silla data since publication year 2000. We make extensive efforts in order to identify all refereed papers that use ESO data including:

- semi-automated screening of journals for ESO-defined keywords using FUSE, a full-text search tool specifically designed for this purpose. At present, the following journals are routinely screened: *A&A, A&ARv, AJ, AN, ApJ, ApJS, ARA&A, EM&P, Icarus, MNRAS, Nature, NewA, NewAR, PASJ, PASP, P&SS, Science;*
- human inspection of each paper that contains at least one of the keywords;
- identification and cross-checking of all instruments and programme IDs used;
- querying of the ESO observing schedule and ESO archive to obtain programme IDs not mentioned in the paper;
- correspondence with authors and instrument scientists in case of doubt.

Therefore, telbib is a unique source that connects published articles with the observing programmes that generated the data. The database is used to derive publication and citation statistics of specific telescopes and instruments and can help to define guidelines for future facilities.

A description of the previous web interface can be found in Delmotte et al. (2005). In December 2011, a new public interface was released, using Apache Solr and PHP. Key features include:

Search interface:
- query by bibliographic information or instrument, telescope and programme ID;
- autosuggest support for author, bibcode, and programme ID searches;
- overview of top five journals and ESO instruments;
- spell-checker for search terms ("Did you mean...?");

Results list:
- paper titles linked to detailed display;
- faceted filtering to limit search results;
- programme IDs linked to data in the ESO archive;
- various options to sort the results;
- export feature for further use of results set;

Detailed record display:
- full list of observing facilities and additional tags;
- highlighted search terms;
- recommendations for other papers of interest.

In the following, we will explain and illustrate the main features of the new features of telbib access. A full description of telbib, the associated full-text search system FUSE, and the new telbib front end can be found in Meakins & Grothkopf (2012).

Search interface

The new public telbib interface offers a wide range of query options for easy access to the information. These include searches for bibliographic information (authors, title words, abstract, publication year, etc.) as well as for observing facilities (instruments, telescopes) and programme IDs. The main search screen provides a dedicated area on the lefthand

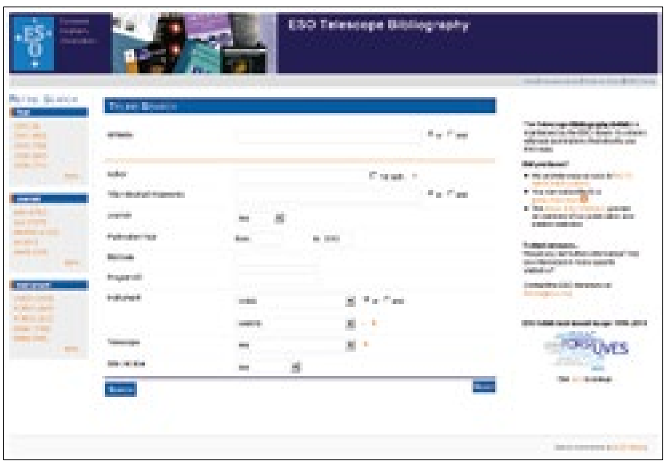

Figure 1. The telbib search interface page is shown.

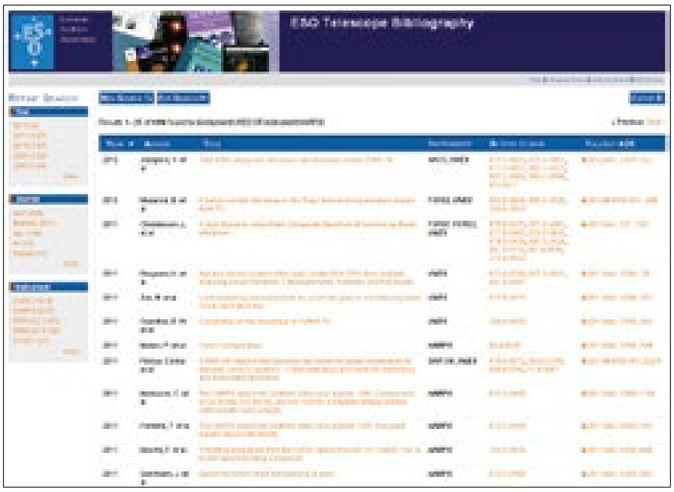

Figure 2. An example results page from a telbib search is shown.

Figure 3. Detailed record display of a bibliographic item using ESO data.

side where the top five journals and instruments are listed, indicating the number of records in telbib for each journal and using data from these instruments, respectively. Similarly, the most recent five years are displayed together with the number of papers per year (see Figure 1).

Certain search fields provide a spell-checker. For instance, if author names or title words entered in the respective fields do not lead to any hits, the system will respond instead with the question "Did you mean…?", followed by suggestions that will turn up results. In addition, after only two characters have been entered in the authors, bibcode, or programme ID fields, an autosuggest feature will start, offering search terms which exist in the index.

Results page

Papers that fulfill the query parameters are displayed on the results page in six columns, showing the publication year, first author, title, instruments, programme ID and the bibcode of each paper (see Figure 2). Titles are linked to the detailed view of records. Programme IDs lead to the ESO observing schedule and from there to the archive where the data can be requested for further use. Bibcodes are connected to the abstracts at ADS from where the full-text versions of articles can be accessed.

Search results can be limited by using the faceted filtering in the "Refine Search" area. Facets are available for publication years, journals, and instruments. For the latter two filters, the top five among these results are shown, together with the five most recent years. Clicking on the "more…" button displays the entire lists. Results sets can be exported into comma-separated (.csv) or tab-separated (.txt) format for further use.

Detailed record display

The detailed record view (Figure 3) shows all ESO observing facilities that were used in the paper, as well as additional tags, indicating, for instance, use of archival data. Search terms are displayed in italics so that they can be easily identified. Instruments, telescopes, and observing sites provide hyperlinks that initiate new searches to retrieve other papers that use the same facilities.

For programme IDs, two links are offered. Clicking on the programme ID itself will evoke a new search for all papers that used data from the same programme. Selecting "access to data" takes users to the observing schedule and from there to the archive where the respective data can be requested if the proprietary period has ended.

Citations are loaded on-the-fly from ADS, hence they are as current and complete as citations at ADS. Links to some papers of similar content to the one currently shown are available at the bottom of the page. This section is entitled "Also of interest?" and invites users to explore the displayed recommendations.

Future enhancements

A search interface, even one that has just been released, is always a work in progress. Consequently, we are already focusing on the next round of improvements.

As statistics are of increasing interest, we are currently investigating the option of a dedicated statistics area which will be accessible from the public search interface. At present, basic statistics derived from the Telescope Bibliography are available through a document located on the Libraries homepage[3]. More specific reports can be provided by the ESO librarians. Soon, users of the public interface will be able to create and visualise statistics based on user-defined criteria, for instance comparisons of specific instruments over a range of publication years.

Feedback on the new telbib interface is very welcome. For questions or suggestions, please contact us at library@eso.org. A more detailed description of the telbib database is available on the web[4]. telbib users who would like to stay informed about newly added papers are invited to subscribe to our RSS feed[5].

Acknowledgements

We are very grateful to Chris Erdmann, now at the Harvard–Smithsonian Center for Astrophysics, Cambridge, MA, USA who created the first versions of FUSE and telbib, as well as Nausicaa Delmotte and Myha Vuong from ESO, for their excellent help and support of the previous telbib front end. FUSE and telbib make extensive use of NASA's Astrophysics Data System.

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Links

[1] ESO Telescope Bibliography: http://telbib.eso.org/
[2] Astrophysics Data System (ADS): http://adsabs.harvard.edu
[3] Some telbib statistics: http://www.eso.org/libraries/edocs/ESO/ESOstats.pdf
[4] On-line help for telbib: http://telbib.eso.org/help.html
[5] ESO libraries RSS feed: http://www.eso.org/sci/libraries/rss.php

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Greetings from the ESO Council

Xavier Barcons[1]

[1] Instituto de Física de Cantabria (CSIC-UC), Santander, Spain

Figure 1. Xavier Barcons pictured in the Council Room at ESO Headquarters.

I am a research professor on the Spanish Council for Scientific Research (CSIC) and was recently elected President of ESO Council, a very high honour and a great challenge for me. I am originally Catalonian, and have been based in Cantabria (in the north of Spain) for most of the last 30 years. My astronomical research is conducted mostly at X-ray wavelengths. Active galactic nuclei, as the signposts of growing supermassive black holes, are my pet objects. I am deeply involved in ESA's X-ray observatory Athena candidate mission, now competing for a launch slot in 2022, and am chair of its science working group. My research activity has slowed down during the last decade as I have been advising the Spanish Government on astronomy matters. On a more personal level, I enjoy sharing experiences with my family (wife Mar, son David and daughter Sara) and long-range mountain biking (e.g., along the Saint James's Way). And yes, I also love watching FC Barcelona play delightful football.

I started to travel frequently to ESO Garching in 2004 when I was asked to negotiate the in-kind deliverables to cover a part of Spain's special contribution to ESO. Spain joined ESO with effect July 2006 (Barcons, 2007) and I was appointed first observer and later government representative on the ESO Council. At ESO I have served in the Observing Programmes Committee, Scientific Strategy Working Group, New Member States Working Group, the Atacama Large Millimeter/submillimeter Array (ALMA) Board, the ALMA Budget Committee and the ALMA Personnel Committee.

At ESO every year is exciting, but maybe not all are equally exciting. In particular 2012 is bound to be an incredibly exciting year for at least three reasons. The first is that we will see the first scientific results from ALMA, now that Early Science observations are underway. It has been very reassuring to see how astronomers in the ESO Member States have massively requested science observations in this first phase of ALMA operations and this will lead no doubt to substantial scientific progress.

Secondly, it is expected that during 2012 the construction of the European Extremely Large Telescope (EELT), "the world's biggest eye on the sky", can be submitted to ESO Council for approval. The Member State delegations are working hard to obtain the funding and approval from their governments for this challenging but captivating project. We are all glad to see that, even in the current difficult economic circumstances, a number of Member States are already prepared to commit funding.

Finally, this is a very special year since ESO is celebrating its 50th anniversary. I recommend reading the preamble of the ESO Convention in order to appreciate the enormous progress achieved in the five decades of ESO's existence. We should take this opportunity to convey to the governments and the full population of our Member States our pride in being able to build the most powerful and productive ground-based astronomical observatories in the world. This achievement is the result of sustained cooperation, a lively community, an enthusiastic staff and a careful balance between operations of world-class facilities and construction of new ones for the benefit of ESO Member States.

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Report on the

ESO Fellows Days in Chile 2011

held at the ESO Offices in Santiago, Chile, 21–25 November 2011

Michael West[1]
Eric Emsellem[1]

[1] ESO

The 2011 ESO Fellows Days were held in Chile and brought together over 30 ESO Fellows from Garching and Chile. As well as presentations of research and social activities, the Fellows Days included a visit to San Pedro de Atacama and the ALMA site.

The ESO Fellows Days were held in Chile from 21–25 November 2011 and brought together more than 30 ESO Fellows from Garching and Chile, as well as the two Heads of the Offices for Science. The purpose of these gatherings is to learn more about the exciting research being done by the impressive group of ESO Fellows in Vitacura and Garching and hopefully to stimulate new scientific collaborations.

ESO Director General Tim de Zeeuw kicked off the meeting with warm words of welcome to the Fellows, reminding them of the importance that ESO places on its Fellowship programme and its value in the development of their careers.

The first three days of the meeting were devoted to short presentations about each Fellow's current research activities. ESO Chile astronomers and students in Vitacura also attended many of the talks.

Figure 1. Social activities on the Fellows Days included lunch and a tour of the Casa del Bosque winery near Santiago.

A special lunchtime talk by Massimo Tarenghi provided an interesting historical and personal overview of the development of the La Silla and Paranal observatories. The programme also included career-training workshops led by the Heads of the Offices for Science on the topics of "Fine-tuning Your Job Applications" and "How to Give a Good Job Interview", with the goal of enhancing the marketability of ESO Fellows and students. A lunch and tour at one of Chile's many wonderful wineries provided a nice opportunity for Fellows to get to know each other better and to gain a deeper appreciation of Chilean culture (see Figure 1).

A highlight of the Fellows Days was a visit to the Atacama Large Millimeter/submillimeter Array (ALMA) on Chajnantor (Figure 2), including an overnight stay in San Pedro de Atacama. Everyone was excited to see ALMA operations in action at the Operations Support Facility (OSF) and the ALMA Operations Site (AOS), and ESO ALMA COFUND Fellow Anaëlle Maury gave a very informative tour of the ALMA facilities. During the visit the Fellows had an opportunity to discover the unusual local ice and snow formations (see the Figure on the Astronomical News section page, p. 37).

Figure 2. More than 30 ESO Fellows and students visited the ALMA site on Chajnantor, accompanied by the Heads of the Offices for Science in Garching and Chile.

Many thanks are due to all the ALMA staff who made this visit possible, and especially to Paulina Jiron of ESO for all her hard work organising the travel and accommodation. We were greatly impressed by the efficiency and professionalism of everyone at ALMA. It's not easy to handle visits by a group of this size to an altitude of 5000 metres, but ALMA managed it perfectly. ALMA hats to block the fierce sun quickly became prized souvenirs for the Fellows and students as a nice reminder of their exciting visit!

The next ESO Fellows Days will take place in Garching during 2013.

Call for Nominations for the European Extremely Large Telescope Project Science Team

The European Southern Observatory invites the astronomical community to nominate candidates for the European Extremely Large Telescope (E-ELT) Project Science Team.

The E-ELT Project Science Team is an advisory working group that will support the E-ELT programme during the construction phase. The E-ELT Project Science Team is not an ESO oversight committee.

Specific tasks of the Project Science Team include responding to specific requests from the Programme Scientist and providing input and advice to ESO and the E-ELT programme to help:
- Refine as necessary the E-ELT science goals;
- Refine, as necessary, the Observatory Top Level Requirements, including the science requirements and performance metrics and objectives for the telescope, the instrumentation, the operations and other scientific aspects of the project;
- Develop the instrumentation plan for the E-ELT and set the scientific priorities for the instrument procurement;
- Develop a science perspective on any major cost/schedule/science trades brought forward by the project.

In addition the Project Science Team is expected to:
- Participate in the E-ELT reviews in order to coordinate scientific requirements

and assist the E-ELT project in decisions as they relate to scientific objectives and the scientific performance of the programme;
– Participate in the refinement of the project science plans and the philosophy for defining and conducting the science programme;
– Disseminate this information actively and explain the goals of the E-ELT to the ESO community.

ESO is seeking a representative group of scientists, covering scientific as well as technical expertise. Candidates should be ready to dedicate more than 10% of their time to the project during the three-year appointment. Funding is available for extended visits (several distributed or continuous weeks) to the ESO Headquarters in the frame of this work.

The closing date for sending nominations is 31 March 2012. The E-ELT programme will start by contacting candidates thereafter, with the goals of completing a team of a dozen multi-disciplinary scientists by 30 April 2012.

Nominations should be justified by a maximum of one page of text, summarising the relevant expertise (and plans) of the candidate for the E-ELT project, and should be submitted electronically to Samantha Milligan (smilliga@eso.org) before 31 March 2012. Both self-nominations as well as nominations by supporters (individuals or groups) are welcome.

The terms of reference for the Project Science Team can be found at http://www.eso.org/sci/facilities/eelt/science/pst

ESO Celebrates its 50th Anniversary

The year 2012 marks 50 years since the ESO Convention was signed by representatives from five European countries — Belgium, France, Germany, the Netherlands and Sweden on 5 October 1962. The anniversary year is an opportunity to look back at ESO's history, celebrate its scientific and technological achievements and look forward to the future.

A number of events and public initiatives are planned for 2012, as announced on the 50th anniversary web page[1], including:
– A scientific symposium (see announcement on p. 47);
– Coordinated public events in the 15 Member States on the day of the anniversary, 5 October 2012;
– A gala anniversary event to take place in Munich on 11 October 2012;
– An anniversary exhibition on display at selected locations in the ESO Member States;
– A documentary film released on the anniversary day, together with an illustrated book;
– The first Picture of the Week[2] of every month in 2012 will be a special Then and Now feature, presenting ESO sites as they looked in the past and as they look today;

– Release of the second part of the official history of ESO, written by Claus Madsen, to follow the book by Adriaan Blaauw, *ESO's Early History* (1991). An illustrated timeline of the five decades of ESO is also available[3].

Links

[1] ESO's 50th anniversary web page: http://www.eso.org/public/outreach/50years.html.html
[2] Picture of the Week: http://www.eso.org/public/images/potw/
[3] ESO Timeline: http://www.eso.org/public/about-eso/timeline.html

Announcement of the Conference

ESO@50 – The First 50 Years of ESO

3–7 September 2012, ESO Headquarters, Garching, Germany

A special science workshop will be held at ESO Headquarters to mark the 50th anniversary. The ESO@50 workshop is intended to provide an original perspective on the scientific challenges of the coming decade, building on the achievements from the science community using ESO facilities. This five-day workshop will focus on the main scientific topics where ESO has made important contributions. Key speakers will be invited to give overviews of each field (including some historical perspective) and then focusing on the present science status surrounding these questions. The next science steps will also be emphasised. Some "bonus" tracks will be included, such as introducing the first ALMA results, the latest unpublished VLT/I and La Silla results, and an outlook for science with the E-ELT.

The meeting will consist of invited reviews and contributed talks covering the many diverse scientific areas in which ESO has contributed, including the Solar System, exoplanets, stellar birth and the interstellar medium, stellar death, the Milky Way, nearby galaxies, galaxy surveys, distant galaxies, galaxy clusters and cosmology.

The distinguished Scientific Organising Committee is composed of: Beatriz Barbuy (Brazil); Xavier Barcons (Spain; president of ESO Council); Willy Benz (Switzerland); Jacqueline Bergeron (France); Emanuele Daddi (France); Tim de Zeeuw (ESO); Eric Emsellem (ESO); Isobel Hook (United Kingdom); Konrad Kuijken (the Netherlands); Bruno Leibundgut (ESO); Maria-Teresa Ruiz (Chile); Monica Tosi (Italy); Linda Tacconi (Germany); Michael West (ESO).

The Local Organising Committee is composed of Eric Emsellem, Bruno Leibundgut, Jorge Melnick, Markus Kissler-Patig, Christina Stoffer, Leonardo Testi, Svea Teupke and Michael West.

The registration deadline is 31 May 2012.

Further details are available at: http://www.eso.org/sci/meetings/2012/ESOat50.html or by email to: ESOat50@eso.org

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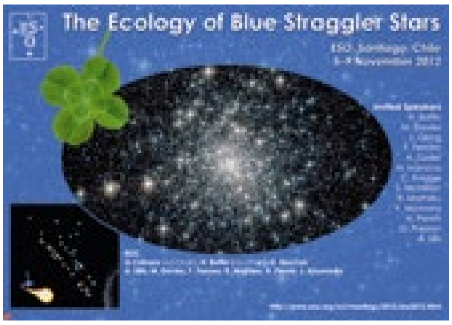
Announcement of the ESO Workshop

Ecology of Blue Straggler Stars

5–9 November 2012, ESO Vitacura, Santiago, Chile



The existence of blue straggler stars, which appear younger, hotter, and more massive than their siblings, is at odds with a simple picture of stellar evolution, as such stars should have exhausted their nuclear fuel and evolved long ago to become cooling white dwarfs. Observations have revealed that blue stragglers exist in globular clusters, open clusters, dwarf spheroidal galaxies (dSph) of the Local Group and OB associations. Field blue stragglers have also been identified from their anomalous kinematics and metallicity.

An accumulation of observational evidence now points to the fact that the two mechanisms thought to be responsible for blue stragglers – mergers and mass transfer – are operating in the same cluster: the exact preponderance of one mechanism over the other possibly depending on the cluster's property, that is, the blue stragglers' ecology. For example, it would seem natural that the most populous systems, i.e. globular clusters, should produce the largest population of blue stragglers, irrespective of the mechanism involved. Recently, however, it was shown that Galactic open clusters seem to contain the largest proportions of blue stragglers, a proportion only approached by the low luminosity dSphs.

This is the first workshop ever devoted to these unique objects. The workshop aims at bringing together theoreticians and observers in order to compose a complete picture of the progress in the field. It will also bring together specialists of binaries and multiple systems, stellar evolution and stellar populations, as well as of the dynamics of clusters. Spread over a week and held at the ESO-Chile headquarters in Santiago, the workshop will consist of extended invited reviews, with ample time for contributed talks and space for posters.

The scientific organising committee is composed of: Giovanni Carraro (ESO, co-chair); Henri Boffin (ESO, co-chair); Giacomo Beccari (ESO); Alison Sills (McMaster University, Canada); Melvyn Davies (Lund University, Sweden); Francesco Ferraro (University of Bologna, Italy); Robert Mathieu (University of Wisconsin, USA); Hagai Perets (Harvard University, USA); and Javier Ahumada (Universidad de Córdoba, Argentina).

The registration deadline is 31 July 2012.

Further details are available at: http://www.eso.org/sci/meetings/2012/bss2012.html, or by e-mail to: bss2012@eso.org

Announcement of the ESO Workshop

Science from the Next Generation Imaging and Spectroscopic Surveys

15–18 October 2012, ESO Headquarters, Garching, Germany

With the addition of the VISTA and VST imaging survey facilities to the La Silla-Paranal Observatory and the start of the selected spectroscopic public surveys, European astronomy has firmly entered the era of large public surveys. The aim of the workshop is to present scientific results from the first two years of science operations of the VISTA public surveys, the first year of the VST public surveys, and an overview of spectroscopic public survey projects at ESO. The first results from the nine ongoing imaging public surveys from VISTA and VST will be featured through invited talks by the survey PIs, as well as contributed talks from survey team members. The scientific usage of public survey data products, including the fulfillment of the science goals of the community based on public survey archive data, will be discussed.

Another goal of the workshop is to put the ESO public survey projects in the context of other ongoing or planned large optical and near-infrared (NIR) imaging surveys, such as SDSS III projects, PANNStaRRs, LSST, SkyMapper, UKIDSS and Gaia, and within the context of spectroscopic surveys carried out at other telescope facilities and/or as follow-up of imaging surveys.

As ESO public surveys cover such a wide range of topics in observational astronomy, this workshop will not concentrate on specific scientific areas, but rather show the exciting new results coming from large surveys and how overall astronomical knowledge can be advanced using public survey data. To this end, contributed talks from scientists who have used public survey data for their own science, but do not necessarily belong to any of the specific groups that have led or executed the surveys, will be encouraged. The topic of data mining and the availability of data products for wide science use by the community will also be discussed. Contributions from open time and guaranteed time observing (GTO) projects on the ESO survey telescopes VISTA and VST will also be welcome. The workshop will include a panel discussion with a forward look on how large collaborations and big projects are organised in other communities.

G. Hüdepohl/ESO

ESO/G. Lombardi

Figure 1. The two ESO survey telescopes: left, the Visible and Infrared Survey Telescope for Astronomy (VISTA) and, right, the VLT Survey Telescope (VST).

The main science topics include:
- VISTA public survey science;
- First results from the VST public survey observations;
- Overview of spectroscopic public surveys at ESO;
- Ongoing and planned large survey projects;
- Synergies between ground-based and space-based surveys;
- Data mining and the availability of survey products for wide science use by the community.

The deadline for registration and abstract submission deadline is 2 July 2012.

Further details are available at: http://www.eso.org/sci/meetings/2012/surveys2012.html or by email to: surveys2012@eso.org

Announcement of the

ALMA Community Days: Early Science in Cycle 1

25–26/27 June 2012, ESO Headquarters, Garching, Germany

ALMA, the Atacama Large Millimeter/submillimeter Array, a global collaboration involving Europe, North America, East Asia and the host country Chile, is currently carrying out first scientific observations for the astronomical community, while construction and commissioning activities continue. The interface between ALMA and its potential users is provided by the local ARC (ALMA Regional Centre). In Europe, the ARC consists of a network of regional ARC nodes coordinated by the central European ARC hosted at ESO Headquarters in Garching, Germany.

ALMA Early Science Operations started with Cycle 0 in September 2011.
Nearly 1000 proposals were received from

ESO/B. Tafreshi (twanight.org)

Figure 1. Panoramic view of the Chajnantor plateau by night, showing many antennas of the Atacama Large Millimeter/submillimeter Array (ALMA).

scientists around the world, around one tenth of which were scheduled for observation. Although the technical capabilities offered in Cycle 0 are limited compared to those envisaged for Full Science Operations, the data obtained are already of remarkable accuracy and quality. In Cycle 1, an enhanced set of ALMA technical capabilities and a larger array of antennas will be offered to the astronomical community. While the building and commissioning of the full array will continue throughout this observing cycle, the fraction of time available for Early Science observations is expected to increase as the array nears completion. Additionally, the higher sensitivity and technical capacity of ALMA in Cycle 1 has the potential to yield ground-breaking scientific results largely surpassing those achievable using existing facilities.

The aim of the 2012 Community Days is to prepare the European astronomical community for Cycle 1 of ALMA Early Science Operations. The first day will feature a series of technical and scientific presentations related to ALMA, the European ARC and capabilities in Cycle 1. The remainder of the workshop will be dedicated to hands-on tutorials focusing on the preparation of Cycle 1 observing proposals using the ALMA Observing Tool (OT). Depending on their level of expertise, the workshop participants will be given the choice of attending either a compact one-day tutorial or a more exhaustive two-day session. This should enable novice and advanced ALMA users alike to create observing projects making full use of the unique capabilities of ALMA during Cycle 1.

Further information can be found at: www.eso.org/sci/meetings/2012/alma_es_2012.html

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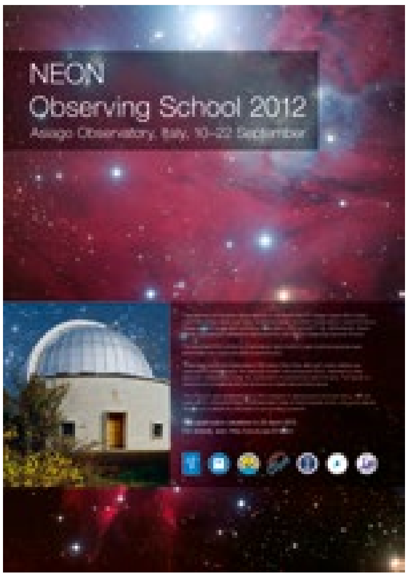
Announcement of the

NEON Observing School 2012

10–22 September 2012, Asiago Observatory, Italy



The Network of European Observatories in the North (NEON: Asiago Observatory [Italy], Calar Alto Observatory [Germany, Spain], European Southern Observatory, Haute Provence Observatory [France], and La Palma Observatory [ING and NOT: UK, the Netherlands, Spain and the Nordic Countries]) is holding the 10th NEON Observing Summer School this year at the Asiago Observatory in the Veneto region of northern Italy.

The purpose of the school is to provide an opportunity to gain practical experience in observation and data reduction in astrophysics. The observing runs will take place at the 1.82-metre Cima Ekar and 1.22-metre Galileo telescopes focusing on modern astrophysical topics. The observations, data reduction and analysis will be conducted under the supervision of experienced astronomers. The hands-on sessions are complemented by lectures on observational techniques.

The school is open preferentially to PhD students and postdocs in astrophysics who are nationals of a Member State or an Associate State of the European Union, but some places will also be available for nationals of surrounding countries.

The application deadline is 20 April 2012.

More details can be found at: http://www.iap.fr/neon/ or by email to: neon2012@iap.fr

Fellows at ESO

Mark Westmoquette

Mark Westmoquette

I think I was around age 16 or 17 and doing my A-level examinations when I developed a serious interest in astronomy. This was due in part to a particularly engaging teacher called Mr Sheldrake, and, in another part (although I hate to admit it now) to *Star Trek*. Moving swiftly on ... My interest grew, such that in 1999 I decided to leave home and go to University College London (UCL) to study astrophysics. Unbeknownst to me then, I wasn't to escape UCL for another 11 years. The undergraduate research project that I did with Linda Smith set me up very well to do a PhD with her on super star clusters, feedback and galactic winds. I then did four years as a postdoc at UCL before being awarded an ESO Fellowship and moving here to Munich.

After my initial naïve and idealistic period of enthusiasm, I have encountered a number of moments in the past ten years when the thoughts of "what's the point of studying astronomy?" and "is it a good use of my life?" have risen to crisis point. One particularly memorable one came just after I'd finished my PhD and was travelling before starting my postdoc. I clearly remember realising that wherever I was, from a dark beach in Costa Rica to a wedding reception in Gloucestershire, people were always fascinated to find out that I study astronomy and often started asking the same fundamental questions about the Universe as I was actually being paid to research. Perhaps it is because the Universe is so vast, so full of wonders (albeit often very complicated and low signal-to-noise wonders), and the "what's out there?" question is so deeply engrained in our human consciousness. This universal interest convinced me that I was doing something meaningful.

I have come to think of studying astronomy as something similar to being an artist or musician. Since it has almost no commercial value — even Google can't sell a galaxy evolution model — its value to society comes solely through curiosity (of our origins), like art whose value is based on curiosity of the human condition. That, in this capitalist world dominated by advertising and profit, with the potential of financial ruin always (and particularly recently) just round the corner, we can still find billions of euros to fund projects of pure curiosity is marvellous! Doesn't knowing that the Sun was born out of an interstellar gas cloud that contained chemicals from many previous generations of stars give more meaning to life than knowing that 37 % of smartphone users use their devices for shopping?

In my opinion, one of the most important things in life is to find a passion and do it 100 %. I feel extremely honoured to be in the position of being able to do that. Not only am I paid to do it, but in academia my passion is continually and actively nurtured. That is part of what makes ESO such an amazing place to work. I'm surrounded on a daily basis by high-flying, brilliant people with high aspirations, and have many possibilities to meet and collaborate with other astronomers in ESO, in the Garching campus or visitors passing through.

My current research focuses on determining the interstellar medium conditions, both within the cores of nearby starburst galaxies and in their resulting feedback-driven winds, with the aim of understanding how these winds are driven and evolve. Integral field units (IFUs) are ideal for studying these complex gas environments, and I have made extensive use of instruments such as VIMOS and FLAMES, and of course the Hubble Space Telescope.

Among my extracurricular interests, yoga and zen are the two most important. One of the highlights of my week is the yoga class I run every Tuesday for ESO staff.

Amelia Bayo

Unlike most astronomers, studying the mysteries of the sky did not even cross my mind when I was a child. I grew up in a "biggish" city in the south of Spain, Malaga, where nobody around me was especially fascinated by astronomy. From a young age, though, as my parents can testify, it was clear that I wanted to do research. I loved discovering new things, and the challenge of tackling a problem until I could find the way to unveil what was going on.

I studied mathematics at Universidad de Malaga and I was leaning towards topology or geometry. But life decided otherwise. I moved to Madrid where the possibilities to do research were way higher. At the Universidad Complutense de Madrid there was a programme for students to participate at the European Space Astronomy Center (ESAC, at that time the Villafranca satellite tracking station) in small summer projects. There was no such thing for pure maths students, so I joined the programme and that is how I got "hooked".

I remember perfectly well the first day I arrived at ESAC. The place was the most advanced technological complex I had ever seen. But this was nothing compared to talking to my supervisor for that little project. ESA staff astronomer, Pedro Garcia Lario, was clearly in love with his research. In less than two minutes he convinced me that one would be out of one's mind not to want to study planetary nebulae! He showed me beautiful images, and he could name plenty of objects by those weird names... I left the office fully convinced that this was the kind of passion I wanted for my career, and so, "astrophysics it was!".

I finished studying mathematics, but with majors in astronomy and then started two Masters, one in artificial intelligence (connected to the Virtual Observatory) and one in astrophysics. With Masters ongoing, it was then time to look for a PhD project.

I learned about an opening for a PhD position at LAEFF; a Spanish laboratory located on the ESAC campus. I went for the interview with David Barrado y Navascues and the experience proved very different from my first day at ESAC. David did not show me the "in love with astronomy" side of him, he showed me the direct and competitive one and let me know very clearly that I was the one asking for a job and that I had to be able to "sell" myself. I was absolutely not prepared for this and I left the office thinking that this will not be "the perfect match" to start a PhD and being pretty sure that he would not offer me the position.

Funnily enough I did get an offer and I could not have been more wrong. No PhD student–supervisor relationship is perfect, but I am convinced that I would not be where I am now in my career (with exactly the job that I wanted to have) without his influence. The first time we went to observe together on La Silla he told me to stay outside for a while and let my eyes get used to the dark. There I found what I had wanted ever since I went to ESAC for the first time: I fell in love with the southern sky, and I decided that Chile and the ESO observatories should become my home very soon.

Amelia Bayo

My main research field is the study of the formation of brown dwarfs, those intermediate objects between stars and planets. Do they form like the stars? Do they form like the planets? How often do they host planetary mass objects? Do their discs evolve similarly to the protosolar disc? To answer these questions we need to compare their properties with those of low-mass stars. During my PhD I studied an extremely interesting star-forming region that hosts clouds of different ages; the λ Orionis star-forming region. In particular, the study of the central cluster (Collinder 69) led to the ensemble of one of the most complete Initial Mass Functions (IMF) for a young association. This allowed us to put constraints on some formation scenarios proposed for brown dwarfs. Besides, the detailed study of the population of sources still harbouring discs in the region allowed us to put caveats on the possibility that a supernova triggered the star formation in the outer clouds.

During my PhD I realised that complete samples are mandatory in order to reach any strong conclusions. Therefore, I joined a very ambitious spectroscopic survey that, using ESO telescopes, will complement Gaia at the lower end of the mass function. On the other hand, to analyse and fully exploit the database that this project will generate, a solid base in astrostatistics and inference is absolutely mandatory. In a sense I am returning to my mathematical background, something I enjoy a lot.

Being at ESO Chile has allowed me to improve my observing skills and to deeply understand some of the instruments that I use for my science. Besides that, and certainly the most important benefit that I will take away from working at Paranal, is the interaction with colleagues and visitors, and the effort required to understand what each service programme needs. All this, I believe, has made me a more complete astronomer. I think that focusing too much on one problem can cause a lack of perspective that can prevent one from finding a solution. Well, being at ESO Chile has had the completely opposite effect on me; I will leave this country with a wider view of astronomy that hopefully will help me to find my answers.

ESO

European Organisation for Astronomical Research in the Southern Hemisphere

ESO Studentship Programme

The research studentship programme of the European Southern Observatory provides an outstanding opportunity for PhD students to experience the exciting scientific environment at one of the world's leading observatories for a period of up to two years.

ESO is the foremost intergovernmental astronomy organisation in Europe. Its approximately 110 staff astronomers, 40 Fellows and 50 PhD students conduct frontline research in fields ranging from exoplanets to cosmology, offering one of the most vibrant and stimulating scientific settings anywhere in the world.

ESO's studentship positions are open to students enrolled in a PhD programme in astronomy or related fields. Students accepted into the programme work on their doctoral project under the formal supervision of their home university, but they come to ESO to work and study under the co-supervision of an ESO staff astronomer, normally for a period of between one and two years. Studentships may be hosted either at ESO's Headquarters in Garching (Germany) or at ESO's offices in Santiago (Chile), where two additional positions per year are provided for students enrolled in South American universities.

Applicants and their home institute supervisors should agree upon and coordinate their research project jointly with their prospective ESO supervisor. For this purpose the ESO supervisor should be contacted well in advance of the application deadline (15 June 2012). A list of potential ESO supervisors and their research interests can be found at http://www.eso.org/sci/activities/personnel.html. A list of PhD projects currently being offered by ESO staff is available at http://www.eso.org/sci/activities/thesis-topics.html.

It is highly recommended that applicants plan to start their PhD studies at their home institute before continuing to develop their research projects at ESO.

ESO Chile students have the opportunity to visit the observatories and to get involved in small technical projects aimed at giving insights into the observatory operations and instrumentation. Such involvement is also strongly encouraged for Garching students. In addition, students in Garching may attend and benefit from the series of lectures delivered in the framework of the International Max-Planck Research School on Astrophysics.

Students who are already enrolled in a PhD programme in the Munich area (e.g., at the International Max-Planck Research School on Astrophysics or a Munich University) and who wish to apply for an ESO studentship in Garching, should provide a compelling justification for their application.

The Outline of the Terms of Service for Students (http://www.eso.org/public/employment/student.html) provides some additional details on the employment conditions and benefits.

If you are interested in enhancing your PhD experience through an extended stay at ESO please apply online at https://jobs.eso.org/. Reference letters to support your application should be sent to vacancy@eso.org for Garching and vacchile@eso.org for Chile.

Please include the following documents in your application:
- a Curriculum Vitae (including a list of publications, if any);
- copies of your university transcript and certificate(s) or diploma(s);
- a summary of your master's thesis project (if applicable) and ongoing projects, indicating the title and the supervisor (maximum half a page);
- an outline of the proposed PhD project highlighting the advantages of coming to ESO (recommended one page, maximum two);
- two letters of reference, one from the home institute supervisor and one from the ESO local supervisor;
- a letter from the home institute that i) guarantees the financial support for the remaining PhD period after the termination of the ESO studentship, ii) indicates whether the requirements to obtain the PhD degree at the home institute have already been fulfilled.

All documents should be typed in English (but no translation is required for the certificates and diplomas).

Closing date for applications is 15 June 2012, and review of the application documents (including the recommendation letters) will begin immediately. Incomplete applications will not be considered.

Candidates will be notified of the results of the selection process during July–August 2012. Studentships typically begin between August and December of the following year.

For further information please contact Christina Stoffer (cstoffer@eso.org).

Although recruitment preference will be given to nationals of ESO Member States (members are: Austria, Belgium, Brazil, the Czech Republic, Denmark, Finland, France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, Switzerland and United Kingdom) no nationality is in principle excluded.

The post is equally open to suitably qualified female and male applicants.

Personnel Movements

Arrivals (1 January–31 March 2012)

Europe	
Allouche, Fatme (RL)	Instrumentation Engineer
Correia dos Santos, Paula Cristina (P)	Software Engineer
Tobar Carrizo, Rodrigo Javier (RCH)	Software Engineer
Tromp, Arnout (NL)	Head of Contracts and Procurement

Chile	
Garrido, Hernan (CO)	Student
Parraguez, Diego (RCH)	Telescope Instruments Operator
Rodón, Javier Adrián (AR)	Fellow
Romero, Rodrigo (RCH)	Telescope Instruments Operator
Tyndall, Amy (GB)	Student

Departures (1 January–31 March 2012)

Europe	
Ahumada, Andrea Veronica (AR)	Fellow
Dall, Thomas (DK)	User Support Astronomer
Lablanche, Pierre-Yves (F)	Student
Nielsen, Lars Holm (DK)	Advanced Projects Coordinator
Pedretti, Ettore (I)	Instrument Scientist
Richichi, Andrea (I)	Instrument Scientist

Chile	
Amira, Maria Soledad (RCH)	Administrative Assistant
Carrasco, Mauricio (RCH)	Student
Drass, Holger (D)	Student
Gutierrez, Fernando (RCH)	Electronics Engineer
Kuo, Caterina (RCH)	Procurement Clerk
Medina, Rolando (RCH)	Electronics Engineer
Nürnberger, Dieter (D)	Operations Astronomer
Olivares, Manuel (RCH)	Telescope Instruments Operator

ESO/B. Tafreshi/TWAN (twanight.org)

The crescent Moon setting over the Paranal Observatory in Chile. The earthshine, which is sunlight scattered off the earth and illuminating the lunar disc, is well seen, as are the planets Mercury and Venus. See Release eso1210 for more details.

Caption to image on page 54 and 55: Near-infrared colour image of the Carina Nebula (NGC 3372) taken with HAWK-I on the VLT. Images in *J*-, *H*- and K_s-bands were combined (colour-coded blue, green and red respectively). The bright star to lower left (south-east) is the massive binary η Carinae. The region to the north-west with many dust clouds is very actively forming stars. More details can be found in Release eso1208 and in the paper by T. Preibisch et al. (A&A, 530, A34, 2011).


ESO/T. Preibisch

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ESO, the European Southern Observatory, is the foremost intergovernmental astronomy organisation in Europe. It is supported by 15 countries: Austria, Belgium, Brazil, the Czech Republic, Denmark, France, Finland, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, Switzerland and the United Kingdom. ESO's programme is focused on the design, construction and operation of powerful ground-based observing facilities. ESO operates three observatories in Chile: at La Silla, at Paranal, site of the Very Large Telescope, and at Llano de Chajnantor. ESO is the European partner in the Atacama Large Millimeter/submillimeter Array (ALMA) under construction at Chajnantor. Currently ESO is engaged in the design of the European Extremely Large Telescope.

The Messenger is published, in hardcopy and electronic form, four times a year: in March, June, September and December. ESO produces and distributes a wide variety of media connected to its activities. For further information, including postal subscription to The Messenger, contact the ESO education and Public Outreach Department at the following address:

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Contents

Front cover: The Helix Nebula, NGC 7293, is shown in the near-infrared from images taken with the VISTA survey telescope in *Y*-, *J*- and K_s-bands (1.02, 1.65 and 2.15 µm respectively). The Helix Nebula, at a distance of 220 parsecs, is one of the closest planetary nebulae and in consequence displays a wealth of fine detail not observed in more distant planetary nebulae. The many compact knots, known from optical observations, emit strongly in molecular hydrogen (detected in the K_s-band image) and trace out in filigree the helix morphology. The outer filament (upper left, north-east) is part of an even larger structure measuring about 2.2 parsecs across. See Release eso1205. Credit: ESO/VISTA/J. Emerson. Acknowledgement: Cambridge Astronomical Survey Unit