

# Shaping E-ELT Science and Instrumentation

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The workshop brought together astronomers from the ESO community, and beyond, with the aim of developing the science cases for the future instrumentation programme for the European Extremely Large Telescope (E-ELT). The two first-light instruments have already been chosen and the workshop focussed on the science cases for the following three instruments. After a review of the instrumentation programmes of E-ELT and the two other ELT projects, the sessions covered the scientific justifications for a mid-infrared instrument, a high resolution spectrograph and a multi-object spectrograph. A session was also devoted to future instrument concepts and other science cases. The workshop concluded with parallel discussions on the multi-object and high resolution spectrograph options and an open discussion.

ESO, working with its member community, has prepared an instrumentation

roadmap for the E-ELT that describes in broad terms the instruments that will be delivered to the telescope over approximately the first five years of operations. The two first-light instruments were selected in 2011: an integral field spectrograph able to exploit the full range of image quality expected by the telescope, from natural seeing to the diffraction limit; and a near-infrared (NIR) camera working at the diffraction limit. Both will be fed by adaptive optics (AO) systems. The next three instruments on the roadmap are a mid-infrared (MIR) camera and spectrograph, a multi-object spectrograph (MOS) and a high spectral resolution spectrograph. Our intention, in organising the workshop, was to hear the community's ideas on the science goals for such instruments.

Such was the enthusiastic response to this meeting, that the first four days of the conference took place at the Bürgersaal in Ismaning, a location that gave sufficient space for the ~160 participants to meet together in one room. During these four days, invited and contributed talks were organised in five sessions, focussing on: (i) the status of the E-ELT, its first-light instrumentation and the status of the other ELT projects; (ii) mid-infrared (MIR) astronomy with the E-ELT; (iii) high resolution spectroscopy (HIRES); (iv) multi-object spectroscopy; and (v) future instrument concepts and science cases. A total of 57 presentations were delivered during these sessions. In addition, 37 posters were presented.

For the final day of the conference, we met at ESO Headquarters in Garching in parallel sessions. Informal discussions concerning ELT-MOS and ELT-HIRES were held in two splinter groups led by Monica Tosi and Gaël Chauvin for the high resolution spectrograph and Isobel Hook and Jordi Cepa for the multi-object spectrograph. Roughly half of the conference participants attended each of these splinter sessions. The outcomes of the splinter discussions were then presented to the plenum before wrapping up the conference with a final, open-themed discussion among all the participants. At the time of writing, the ESO E-ELT Science Office, working with the ELT Project Science Team, is taking the input from this workshop and other

sources to define the requirements for the next capabilities on the E-ELT to follow on from the first-light instruments.

## E-ELT projects and first-light science

Following an introduction from the ESO Director General, Tim de Zeeuw, an afternoon of presentations on the E-ELT project and instrumentation was complemented by presentations on the instrumentation plans for the Thirty Meter Telescope (TMT), by Luc Simard, and for the Giant Magellan Telescope (GMT), by George Jacoby. The revised instrumentation roadmap for the E-ELT was presented by Mark Casali. Following the launch of the contracts for the first-light instruments, the intention is that the procurement of the next three instruments will proceed in parallel. Detailed presentations on the first-light instruments were made by the principal investigators (PIs), Niranjan Thatte for the HARMONI integral field unit (IFU) spectrograph and Ric Davies for the MICADO camera. The MICADO camera is planned to be used with the multi-conjugate adaptive optics system, MAORY, the status of which was presented by the PI, Emiliano Diolaiti. A glimpse of two of the scientific programmes that will benefit from the first-light instruments was given by Chauvin, who discussed the potential for exoplanet science, and Seppo Mattila, who showed the future impact of adaptive optics observations on supernova research. The applications of an AO-fed camera on the E-ELT to the studies of blue compact dwarf galaxies and globular clusters were discussed later by Giuliana Fiorentino and Annalisa Calamida respectively.

The core of the workshop then consisted of sessions on the science cases for the three instrument concepts, summarised in following the sections.

## Mid-infrared astronomy with the E-ELT

Based on the Phase A instrumentation studies, the MIR imager and spectrograph has been selected to be built for the E-ELT as one of the instruments to follow after the first-light pair. The concept and science cases for this instrument were presented in a review by the

PI, Bernhard Brandl. A review by Joana Ascenso and João Alves then covered the expected impact of the E-ELT on MIR studies of all stages of star formation from cores to star clusters. The third and final review talk was on MIR observations of evolved stars by Martin Groenewegen, confirming again the importance of the high spatial and spectral resolving power that will make MIR astronomy on an ELT a powerful complement to James Webb Space Telescope programmes.

The theme of stars and star formation was then taken up by the contributed talks, covering simulations of star cluster observations (Andrea Stolte), further exploration of the theme of evolved stars by Josef Hron and the potential for studies of high-mass young stellar objects (René Oudmaijer). Miwa Goto showed some of the advantages of IFU spectroscopy for studies of circumstellar discs. Exoplanet science is one of the cornerstones of the science case for the E-ELT. This was considered from two angles in the context of the MIR instrument by Wolfgang Brandner, who discussed the direct imaging of exoplanets, and by Ignas Snellen, who showed how the combination of high resolution MIR and NIR spectroscopy can allow the characterisation of exoplanetary atmospheres for a range of planets, possibly even for exo-Earths.

### Galactic and extragalactic astronomy with HIRES

The Galactic and extragalactic cases for a future HIRES instrument were discussed in separate sessions on Tuesday afternoon and Wednesday morning. As might be anticipated, a wide range of science topics was presented.

The Galactic session was opened by an intriguing review from Jay Farihi on the archaeology of exoplanetary systems. The study of exoplanets also featured significantly in the interests of the contributing speakers, with a further talk on the possibilities of characterising exoplanet atmospheres from Nuno Santos, a presentation on the synergy between an ELT high spectral resolution spectrograph and the future Next Generation Transit Survey (NGTS) and CHaracterising

ExOPlanets Satellite (CHEOPS) missions from Didier Queloz. The potential for detection of exoplanets in the Bulge and in external galaxies was presented by Eike Günther, who proposed investigating the fraction of stars hosting high-mass planets as a function of stellar density and galactocentric radius, testing the effect of environment on planet formation.

Closer to home, Paolo Molaro presented the detection of the Rossiter–McLaughlin effect in the transit of Venus in June 2012 and demonstrated that in principle this effect could be detected against the stellar jitter even for Earth-like planets (see Molaro et al., p. 22). As well as exoplanetology, a HIRES on the E-ELT will be important for the studies of stars themselves, as stressed by Livia Origlia, who showed first results from the NIR high resolution spectrograph recently installed at the Telescopio Nazionale Galileo (TNG), and also for the many physical processes accompanying star formation. Leonardo Testi showed that a HIRES will allow detailed study of winds from the outer disc, photo-evaporation from the inner disc, gas content and kinematics of the jet and inner disc, and the evolution of accretion of material from the disc onto the star.

During the extragalactic session, Valentina D’Odorico reviewed the importance of high resolution spectroscopy on an ELT for understanding the metal enrichment history of the intergalactic medium. The evolution of the abundance, ionisation state and spatial distribution of metals can discriminate between different mechanisms by which metals can theoretically be transported from galaxies into the intergalactic medium (IGM). In Max Pettini’s review, he expanded on two cases for studying the most metal-poor objects in the Universe with high resolution spectroscopy. A HIRES on an ELT will provide full chemical fingerprints of old, extremely metal-poor stars in the Milky Way, and will also allow detailed study of the abundances of metals, including Fe-peak elements, in near-pristine gas (detected as very low-metallicity damped Ly $\alpha$  systems [DLAs]) at high redshift.

The contributed talks in the extragalactic session then covered key areas of the science expected from the E-ELT. Stefano Cristiani and Pauline Vielzeuf

discussed the use of observations of the redshift drift and possible variations in the fine structure constant ( $\alpha$ ) and of the electron-to-proton mass ratio ( $\mu$ ). Martin Haehnelt reviewed the case for using faint but densely spaced background sources (quasi-stellar objects [QSOs] or Lyman-break galaxies) to probe, in absorption, the immediate environment of galaxies and to study the interplay between galaxies and the IGM. Sandra Savaglio highlighted super-luminous supernovae (SLSNe) as targets for intermediate to high resolution spectroscopy with the E-ELT. Apart from their significance as the end product of the evolution of very massive (50–250  $M_{\odot}$ ) stars, the comparatively slow evolution of SLSNe compared to gamma-ray bursts makes them excellent background sources for high-redshift interstellar medium studies.

In addition to the talks on individual science topics, Roberto Maiolino presented an overview of the science cases for a high resolution spectrograph.

### Multi-object spectroscopy on the E-ELT

The session on MOS with the E-ELT took place on the Wednesday afternoon and continued on Thursday morning. A broad range of invited and contributed papers covered topics from the re-ionisation of the Universe to spectroscopy of extremely metal-poor stars.

James Dunlop reviewed the potential for MOS studies of the evolution of galaxies at high redshift ( $6 < z < 10$ ) and their ability to re-ionise the Universe. Olivier Le Fèvre added to the case for E-ELT observations at these redshifts with a talk on the first phases of galaxy formation and assembly, showing that the E-ELT has the potential to provide large samples of observations at  $z > 7$ , enabling a robust statistical comparison with what is done today at  $z \sim 2$ –3. Jean-Paul Kneib discussed using lensing by massive galaxy clusters for studies of the first galaxies, while José Afonso showed that follow-up of future radio surveys, like the Low-Frequency Array (LOFAR), the Evolutionary Map of the Universe (EMU) and the Westerbork Observations of the Deep APERTIF Northern-Sky (WODAN), is another tool with which to probe galaxy

formation. At lower redshift, Hector Flores argued that spatially resolved kinematics in  $z > 1.5-2$  galaxies are required to study a large number of normal galaxies in order to investigate their star formation, dynamical state and the evolution of the fundamental scaling relations.

François Hammer and Jean-Gabriel Cuby discussed the use of both high-multiplex MOS spectroscopy and spatially resolved spectroscopy with lower multiplex, but supported by AO correction of the atmosphere, to observe the mass assembly of galaxies over the last twelve billion years. An instrument concept with potential to provide both these capabilities, and with science cases including the role of high- $z$  dwarf galaxies in galaxy evolution, tomography of the IGM, resolved stellar populations beyond the Local Group and Galaxy archaeology with metal-poor stars, was presented by Chris Evans and Lex Kaper. Dimitri Gadotti further argued the case for observing the different components of galaxies (e.g., disc [thick/thin], bulge, bar, rings, etc.) with multiple, deployable IFUs.

The importance of a MOS instrument for stellar studies was first explored through review talks from Danny Lennon and Norbert Przybilla. Lennon covered the topic of massive stars, developing ideas of how their formation, evolution and death can be determined by MOS observations in nearby galaxies. Przybilla specifically discussed the study of supergiants out to the distance of the Virgo and Fornax clusters, which would be enabled by a MOS on the E-ELT. Locally, spectroscopic studies of the Galactic Bulge and its globular clusters can shed light on various possible scenarios of bulge formation and on the early phases of galaxy formation (Beatriz Barbuy). Much of the potential of the E-ELT extends this work to nearby galaxies, including resolved populations in the Local Group (talk by Thierry Lanz). With an ELT, Stefano Zibetti showed that studies of the formation and chemical evolution of stellar populations in galaxies can be extended to  $z \sim 3$ . Reaching the required sensitivity to absorption features that are diagnostics of age and metal content is currently extremely challenging at  $z \sim 0.7$  with 8-metre-class telescopes. Studies of extremely metal-poor stars in external



Figure 1. The workshop participants in the entrance hall at ESO Headquarters.

galaxies, down to the main sequence turn off, can give us information on the critical metallicity needed to form low-mass stars and therefore on the mass distribution of the first generation of stars (Piercarlo Bonifacio). Ben Davies discussed using the chemical composition of large samples of stars at Mpc distances to obtain a more reliable determination of distances and metallicities than those based on Cepheids, or those derived from H II regions and colour-magnitude diagram fitting.

#### Future instrument concepts and science cases

The final formal session of talks on Thursday afternoon was open for presentations of instrument concepts and observing techniques that would either extend the ideas already under study for the HIRES and MOS instruments, or offer possibilities for the next instruments on the roadmap.

Roland Bacon presented the idea of a MUSE-like wide-field IFU spectrograph to survey for Ly- $\alpha$  emission from dense filaments of the IGM induced by the ultraviolet cosmic background. Martin Roth showed a concept for increasing the detectability of sources in highly crowded fields using crowded-field 3D spectroscopy — a technique analogous to crowded-field photometry — in a presentation which included tests of this technique on Potsdam Multi-Aperture Spectrophotometer (PMAS) data. Dainis Dravins explained how the large collecting area of the E-ELT could be used as

an intensity interferometer and how this technique could potentially deliver science even during the construction phase of the telescope. Roberto Ragazzoni presented his ideas on adaptive optics using only natural guide stars on the E-ELT. The potentially important role of polarimetry was presented by Klaus Strassmeier. Finally, in a talk scheduled in the Wednesday morning session, Markus Kasper presented the roadmap towards the E-ELT Planetary Camera and Spectrograph, the workhorse instrument to reach the ultimate sensitivity for exoplanet characterisation.

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#### Links

Webpages with the poster and oral presentations from the meeting are available at <http://eso.org/sci/meetings/2013/eelt2013/program.html>.