The big picture

Interspersed throughout the conference were summary reviews of the established planet formation mechanisms invoked to describe the formation of the Solar System and known exoplanets, and how they are both challenged and supported by the new results (Hilke Schlichting, Ruth Murray-Clay and Benjamin Bromley). Overall, it was clear from the superb images, the models, and the discussions held during the meeting that the new high-resolution facilities are transforming our understanding of the field. An audience vote on the newly discovered disc structures favoured their being caused by a combination of protoplanets as well as complex disc physics and chemistry. We can expect many more fascinating high-resolution results in the next few years. The challenge is to link these results with planet formation models as well as with the zoo of exoplanets now being discovered.

Most of the talks and posters are available on the conference website[1]. They are also available through Zenodo[2] and linked through the Astrophysics Data System (ADS[3]).

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Casassus, S. et al. 2013, A&A, 553, 64
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Links

[1] Workshop website: http://www.eso.org/sci/meetings/2016/Planet-Formation2016/
[2] Zenodo: http://zenodo.org/
[3] ADS: http://adsabs.harvard.edu/

Report on the ESO Workshop

Very Large Telescope Adaptive Optics Community Days

held at ESO Headquarters, Garching, Germany, 20–21 September 2016

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The future of adaptive optics (AO) instruments at the VLT was discussed during a two-day workshop. Three major directions emerged from these discussions: adaptive optics in the optical; multi-object adaptive optics (MOAO); and extreme adaptive optics (XAO). The science cases for these three options were presented and the discussions are summarised. ESO is now planning to provide detailed science cases for an optical AO system and to prepare upgrade plans for XAO and MOAO.

Introduction

ESO is planning the future of adaptive optics with the Very Large Telescope (VLT). With the Adaptive Optics Facility (AOF; Arsenault et al., 2010, 2014, 2016), the VLT will deploy a powerful tool for correcting the distorting effects of the Earth's atmosphere. As part of the AOF, the GRound layer Adaptive optics Assisted by Lasers module (GRAAL) will provide a wide-field (7 × 7 arcminute) ground-layer adaptive optics imaging system for the High Acuity Wide field *K*-band Imager (HAWK-I). Also part of the AOF, the Ground Atmospheric Layer Adaptive optiCs for Spectroscopic Imaging module (GALACSI) will provide two modes of optical corrections for the Multi Unit Spectroscopic Explorer (MUSE), one providing a doubling of the encircled energy over the 1 × 1 arcminute field-of-view of MUSE, and the other with a narrow field (7.5 × 7.5 arcseconds) with at least 5 % Strehl ratio at 650 nm for the MUSE narrow field mode. The Enhanced Resolution Imaging Spectrograph (ERIS) will complement the instrument suite on Unit Telescope 4 (UT4) offering *J*-, *H*- and *K*-band integral field spectroscopy and *J*- to *M*-band imaging with a single-conjugate AO (SCAO) system with high Strehl ratio.

The VLT AO Community Days provided an opportunity to discuss the future of AO at the VLT. The aim was to explore the scientific goals of a new instrument to make good use of the AOF, ideally while complementing the European Extremely Large Telescope (ELT) capabilities. There were 54 registered participants at the Community Days and the programme, with links to the presentations, is online[1].

The VLT AO Community Days started with an overview of the existing and planned AO instrumentation on the VLT (see Table 1). Major development paths for multi-conjugate adaptive optics (MCAO), multi-object adaptive optics (MOAO) and extreme adaptive optics (XAO) were presented. MCAO corrects more than one turbulent layer in the atmosphere and can achieve corrections over a larger field-of-view than single-conjugate adaptive optics systems, like NAOS-CONICA (NACO) and ERIS, are able to. ESO deployed an MCAO test instrument in 2007 (the Multi-conjugate Adaptive optics Demonstrator — MAD; Marchetti et al., 2007). In MOAO several non-contiguous fields are corrected individually so as to permit observing over a wider area. XAO reaches the highest density of correction over a small

Name	Year starting operation	Instrument modes	Field of view	Comments
NACO	2002	Imaging: *JHKsL′M′* Spectroscopy: 0.9–2.6 μm Coronagraphy Polarimetry	14 × 14″ 28 × 28″	NIR wavefront sensor; to be decommissioned in 2019
SINFONI	2004	Integral field spectroscopy: 1.1–2.45 μm	3 × 3″ 0.8 × 0.8″	To be upgraded for use with AOF as part of ERIS
SPHERE	2015	Imaging: 0.95–2.3 μm Spectroscopy: 0.95–2.3 μm Coronagraphy Imaging & polarimetry: 500–900 nm	11 × 11″ 3.5 × 3.5″	On-axis correction only
HAWK-I	2018	Imaging: *JHK*	7 × 7′	Ground-layer AO
MUSE	2018	Integral-field spectroscopy: 480–930 nm	1 × 1′ 7.5 × 7.5″	Optical ground-layer AO Optical laser tomography
ERIS	2020	Imaging: *J*–*M′* Integral-field spectroscopy Coronagraphy: *L*-, *M*-bands	27 × 27″ 54 × 54″ 8 × 8″	

Table 1. VLT AO instruments and AO-assisted instrument modes.

field-of-view and the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) is currently the VLT instrument serving this need.

A discussion session at the end of the first day of the meeting was used to clarify several issues connected to adaptive optics. The importance of astrometry, the potential of new noiseless detectors, and different metrics for image quality were part of this discussion. The distinctions between Strehl ratio, full width at half maximum, encircled energy and image stability can be of particular importance to individual science cases. The definition of a new instrument will have to clearly specify the important parameters in terms of image quality. The second day began with a general introduction to future directions of adaptive optics, which was followed by several presentations on specific science cases for the AO modes described above. An open discussion at the end of the second day was used to collect opinions on the different science cases and the scientific promise they provide.

Science with adaptive optics

The science cases for new adaptive optics instrumentation cover several broad topics. Adaptive optics has opened up the study of the close environments of stars (circumstellar discs and exoplanets) and this is clearly the realm of XAO. Other science topics addressed by such instruments are star formation and evolution as well as the formation of planets and planetary systems. SPHERE is currently proving very effective for such observations in the near-infrared and at optical wavelengths, producing a stream of publications (16 publications in 2015 and 22 already in 2016 at the time of writing). A second case is the study of stellar populations in nearby resolved objects — stellar clusters and (dwarf) galaxies in the Local Group and beyond. The important parameter for this research is the concentration of the stellar light into stable point spread functions (PSFs) which ensure accurate photometry and astrometry. Since the spectral energy distribution of most stars peaks in the optical, short wavelengths are important for this science case. The example of MAD near-infrared observations combined with optical Hubble Space Telescope (HST) imaging shows the power of a wide wavelength range (for example, Ferraro et al., 2009; Fiorentino et al., 2011). This is a typical MCAO application.

The third science case deals with resolved objects, typically at large distances, where the improved image quality allows one to analyse individual regions in galaxies rather than only the global parameters (for example, Förster Schreiber et al., 2014; Genzel et al., 2014; Troncoso et al., 2014). The galaxies are, however, sparsely distributed on the sky and a non-contiguous corrected field must be considered. Important clues to the history of star formation are provided by the morphologies of galaxies observed in the local Universe, in particular their discs. An instrument like the *K*-band Multi Object Spectrograph (KMOS) could be supported through an AO module in such a case (MOAO). Other emerging AO applications discussed at the Community Days were: astrometry, for example to measure proper motions of individual stars or to search for stellar-mass black holes in nearby stellar systems; time domain observations in crowded fields (comparing variable stars in the field and in clusters; unique events like the flares around the massive black hole at the Galactic Centre); and the use of adaptive optics to push the limiting magnitude for point sources.

There was general agreement that SPHERE represents an ideal basis for future upgrades. Several potential upgrades were mentioned, such as a pyramid wavefront sensor to reach fainter reference stars; higher correction frequency; fibre coupling to the CRyogenic InfraRed Echelle Spectrometer [CRIRES]. A fibre link to the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations [ESPRESSO] has also been proposed recently as well. These options would push the contrast sensitivity of SPHERE towards reflected-light planets, and the high-resolution spectroscopy would enhance the capability to characterise exoplanet atmospheres. These items should be discussed as part of an upgrade planning of VLT instruments.

The galaxy-formation MOAO science case is an extension of the (large) programmes currently running with KMOS, targeting spatially resolved star formation in high-redshift galaxies and the kinematics of stars and gas in the precursors of present-day galaxies. With improved angular resolution, the individual parts of galaxies, such as giant HII regions, discs, in/outflows and their kinematics, could be resolved and investigated. The number density of these objects is fairly small, expected to be about five objects per 3 × 3 arcminute field with K_{AB} < 20.0 mag, which makes the multiplex gain rather small. Upgrading KMOS with a corresponding AO module is difficult, as the current spaxel size (0.2 arcseconds) is too coarse for AO-supported images, while reimaging may lead to integrated field unit (IFU) fields of view that are too small for the typical galaxy sizes (< 2 arcseconds). At the moment it is unclear whether a sufficient multiplex could be reached to give a significant advantage over single-object observations with SINFONI. MOAO should be discussed in the context of future instrument upgrades.

Resolving stellar populations implies observing individual stars in other galaxies in two or more filters and placing the measurements in a colour-magnitude diagram (CMD). This requires a combination of high angular resolution and high flux sensitivity. Adaptive optics can extend the reach to larger distances and also into denser regions. Contiguous fields with good, but not necessarily excellent, correction can provide the necessary statistics. A useful field-of-view is defined as one which provides measurements of a sufficient number of stars to populate a CMD, corresponding to roughly the diameter of the half-light radius in globular clusters in the Milky Way, i.e. about 1 arcminute. A wide wavelength range clearly benefits the interpretation of a CMD and in particular access to optical wavelengths would make a big difference. Pushing to wavelengths as blue as 500 nm would include observations of some important emission lines (for example [O III]) and also cover the peak of the blackbody curve of common G type stars. An important issue is the photometric accuracy that the system should deliver. A typical uncertainty that can be accepted is ~ 0.03 magnitudes. The magnitude difference for multiple main sequences in globular clusters is < 0.02 magnitudes. The field-of-view of existing and planned optical AO systems at the VLT is very limited: SPHERE with ZIMPOL (the Zurich IMaging POLarimeter) offers 3.5 × 3.5 arcseconds and the narrow-field mode of GALACSI with MUSE provides 7.5 × 7.5 arcseconds.

Additional considerations

The AO applications at the VLT should be seen in the wider context of imaging and spectroscopy with high image quality. Table 1 gives a flavour of the AO-supported instrumentation at the VLT in the next decade. Only NACO is scheduled to be retired by then and its capabilities will be superseded by ERIS. The ELT will provide superior image quality at near-infrared wavelengths with the first-light instruments MAORY (the Multi-conjugate Adaptive Optics RelaY), MICADO, and HARMONI. It is noteworthy that the diffraction limit of an 8-metre telescope at 500 nm corresponds to the diffraction limit of a 40-metre telescope at 2.2 µm.

HST will continue in operation until the scientific return diminishes, or it can no longer be maintained. It can be assumed that a few years into the operation of the James Webb Space Telescope (JWST), HST will cease to offer observing time. This will end over two decades of high-angular-resolution imaging in the ultraviolet and optical. JWST will cover the near- and mid-infrared wavelengths with improved image quality once it starts operating in 2019. By 2025, Gaia will have provided an astrometric coordinate frame covering the whole sky and Euclid and LSST will have mapped large fractions of the sky (to about 25th magnitude).

Some technical developments are also changing the landscape. In particular, new infrared detectors for wavefront sensing with exquisite noise performance will allow reference stars to be pushed to fainter magnitudes. The functionality of MEMS (micro-electro-mechanical systems) opens up new possibilities. They could be used to dissect the field-of-view into individually corrected sub-fields by an innovative use of the lasers, to replace the deformable mirror for atmospheric correction — potentially also in open loop — and as configurable slit masks.

Summary

There was general consensus at the VLT AO Community Days that an upgrade path for SPHERE should be defined to further develop XAO at the VLT. Clearly, the next-generation XAO instrument needs to be on the ELT. The science cases for reduced inner working angle and higher-contrast imaging are based on exoplanet characterisation and star formation research. The MOAO case is mostly focused on galaxy formation and evolution. The exact multiplex needed for this latter science case is unclear. Statistically significant samples (several hundred galaxies, if possible) are required for a detailed mapping of the star formation history and the dynamical changes of galaxies over cosmic time. The MCAO case for optical and infrared wavelengths appears to offer the biggest gain for future AO on the VLT. Optical AO has only recently started, but is already providing interesting results (for example, SPHERE/ZIMPOL, MagAO at Magellan and the recent tests with the Gemini Multi Object Spectrograph [GMOS] and the Gemini Multi-conjugate adaptive optics System [GeMS]).

The outcome of the VLT AO Community Days was presented to the La Silla Paranal subcommittee of the Scientific Technical Committee (STC). The STC recommends pursuing the studies for a new optical/near-infrared MCAO system and upgrade paths for SPHERE and KMOS. These studies should be presented to the STC in the coming year so that it can issue recommendations on the respective scientific merits.

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Links

[1] Programme of VLT AO Community Days: http://www.eso.org/sci/meetings/2016/VLTAO2016/program.html