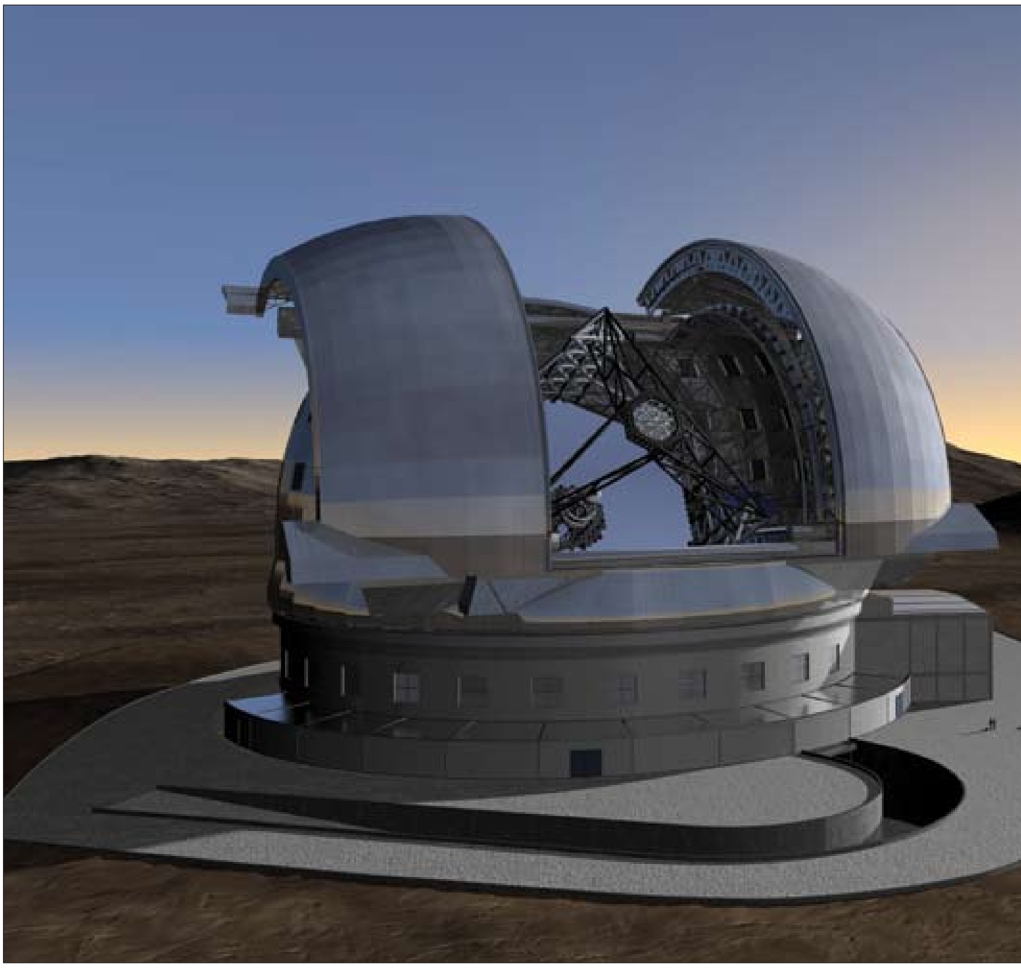
The European Extrem

Chris Evans reports on plans for the world's largest optical–infrared telescope, as discussed at the RAS Specialist Discussion Meeting held on 9 May 2008.



In December 2006 the European Southern Observatory (ESO) initiated a three-year Phase B Study of a 42 m E-ELT (Gilmozzi and Spyromilio 2007). Over the past 18 months there has been healthy progress on the design of the telescope, its enclosure, the interface with the instrument suite, and the infrastructure required to access and service the facility. In parallel, development of an inclusive science case has continued and, most recently, six Phase A instrument studies have started, four of which feature UK partners. In the light of such activity, the RAS Specialist Discussion Meeting was a timely opportunity to provide an update to the UK community on the E-ELT project.

Over the past five years the E-ELT science case has been developed by a substantial segment of the European astronomical community, largely under the auspices of the FP6 OPTICON network led by Gerry Gilmore and Isobel Hook. The E-ELT will make a unique contribution to our understanding of the universe over all scales, as illustrated by the nine "Prominent Science Cases" identified by the E-ELT Science Working Group in April 2006:

- Exoplanets
- Stellar discs
- The initial mass function in stellar clusters
- Resolved stellar populations
- Black holes/AGN
- The physics of galaxies
- Metallicity of the low-density IGM
- The highest-redshift galaxies
- Dynamical measurement of universal expansion.

These cases now form the basis of a "Design Reference Mission" (DRM) – a set of observing proposals and simulated data that is being developed in order to inform design trade-offs for the telescope and its instrumentation. The DRM topics deliberately span the widest possible parameter space for discoveries, including the requirement for extreme adaptive optics (AO), ultra-stable spectroscopy, natural-seeing observations and a mid-IR capability. Of course, these are just examples of potential E-ELT science that we can imagine doing now – in practice the telescope is almost certain to surpass these with discoveries that we cannot even conceive of, as proved to be the case when moving up from 4 m to 8 and 10 m class telescopes. As an illustration of some of the science the UK community is proposing for the E-ELT, there were four contributed science talks at the RAS meeting, spanning observations of galactic star clusters right out to the most distant, "first-light" galaxies.

ABSTRACT

The European Extremely Large Telescope (E-ELT) is in its detailed design phase. With an unprecedentedly large primary aperture and correction for ground-layer atmospheric turbulence, the telescope will offer a tremendous leap forward in our ground-based capabilities. An RAS Discussion Meeting provided updates on the telescope design, its science case and UK involvement in instrument studies.

1. Stellar clusters near and far

The stellar initial mass function (IMF) appears to be invariant over a vast range of scales and environments, e.g. in massive stellar clusters (Bastian *et al.* 2006). However, in some special circumstances we still find statistically significant variations (Elmegreen 2008). Understanding this empirical law has huge implications for our interpretation of star formation at *all* redshifts. With the E-ELT we will be able to explore directly all the known star clusters in the Milky Way down to the lowest stellar masses, as well as penetrating the dense, obscured regions in the inner parts of the galaxy – will we still find evidence for IMF variations? With the E-ELT we will also gain new views of clusters in Local Group galaxies (e.g. using spatially resolved IFU spectroscopy to map their dynamics) and we will have access to high-quality imaging and spectroscopy of clusters far out into the Local Volume, using them, for example, as tracers of the star-formation history in interacting galaxies such as NGC 3256 at 36 Mpc (Trancho *et al.* 2007).

2. Studies of gamma-ray bursts (GRBs) and their host galaxies

The past decade has been exceptionally fruitful for studies of GRBs. The Swift satellite in particular has provided a wealth of detections (~100/yr)

ely Large Telescope

1: Conceptual design of the E-ELT. (ESO)

since its launch in 2004. Rapid-response, ground-based, spectroscopic follow-up of GRBs has been crucial for characterizing their distances; the median redshift from the Swift bursts is $z=2.3$ (Fynbo *et al*. 2007), with the largest redshift, to date, $z=6.3$ (Kawai *et al*. 2006). Were we to have the E-ELT today, studies of GRBs would benefit hugely from the increased sensitivity – high spectral-resolution follow-up would become routine and early-stage, time-resolved observations would be possible, even for the shortest, most elusive bursts. New high-energy space missions are now at the planning stages and, if funded, will provide a wealth of GRBs and other transient sources in need of follow-up in the ELT era. Additionally, there are now positions for thousands of GRBs in the literature – the high angular-resolution of the E-ELT will allow us to explore the host galaxies of these bursts and the stellar populations in their vicinity.

3. The assembly and evolution of high-redshift galaxies

One of the prime goals in modern astronomy is to understand the formation and evolution of galaxies. It is clear that much of the star-formation and "assembly" of these galaxies occurred over the redshift range $1<z<5$, but the processes behind this evolution remain unclear, particularly the effects of galaxy interactions or mergers and feedback from supernova explosions and AGN. Recent observations have demonstrated the power of spatially resolved spectroscopy via AO-fed IFUs to measure physical parameters such as masses, star-formation rates and the presence of outflows in distant galaxies, e.g. Genzel *et al*. (2006) and Law *et al*. (2007). However, this has only been possible for the brightest/largest galaxies at these redshifts. The E-ELT will allow us to compile representative samples over a much wider range of luminosities, to gain a precious insight into the origins of the galaxies we see around us in the present day, local universe.

4. Studying the first galaxies

New observations of galaxies at redshifts $5<z<6$ find that large stellar masses are already in place (McLure *et al*. 2008). This suggests that significant star formation must have occurred at even greater redshifts. Observational constraints on the properties of galaxies at $z>6$ are scarce, with only a handful confirmed via spectroscopy of their Lyman-α emission (e.g. Iye *et al*. 2006). Candidate galaxies at higher redshifts are now being found from new imaging surveys (e.g. Bouwens *et al*. 2008), but we lack the sensitivity for spectroscopic confirmation and analysis of these. The E-ELT will enable us to obtain quantitative information on the properties of these galaxies for the first time. Estimates of their star-formation rates, sizes and morphologies will provide insight into the growth and activity of galaxies in the early universe, with a view to understanding the processes responsible for reionization.

And much more...

Unfortunately it was impossible to span the full range of E-ELT science in a one-day meeting. For instance, one of the most headline-worthy (and technically demanding) objectives of the E-ELT is the detection and characterization of exoplanets. More than 200 exoplanets are now known, most of which have been discovered by indirect methods such as radial-velocity and transit searches. The planets discovered so far are generally very different to planets in our own solar system – this is most likely to be a selection effect in that we are only sensitive to the most massive or eccentric objects. The arrival of high-contrast imagers on 8–10 m class telescopes (e.g. VLT-SPHERE and Gemini-GPI) will herald a new era in exoplanet studies – their sensitivities and potential contrast-ratios should be sufficient to detect warm, self-luminous, Jovian-mass planets in the solar neighbourhood *directly*. The E-ELT will provide the next leap forwards, extending our grasp to mature planets that are similar to those in our own solar system and maybe even into the regime of rocky planets in the habitable zones of their parent stars.

The telescope

ESO's Baseline Reference Design (BRD) for a 42 m telescope was presented to the community at the "Towards the European ELT" conference in Marseille in November 2006. Significant progress has been achieved over the past 18 months, with ESO now consolidating the design work to converge on a construction BRD by the end of 2008; the latest conceptual design is shown in figure 1. To put a 42 m primary aperture into context, it will have an equivalent area of seven tennis courts or, if you favour a more London-centred reference scale, has a diameter equivalent to five Routemaster double-deckers parked end-to-end!

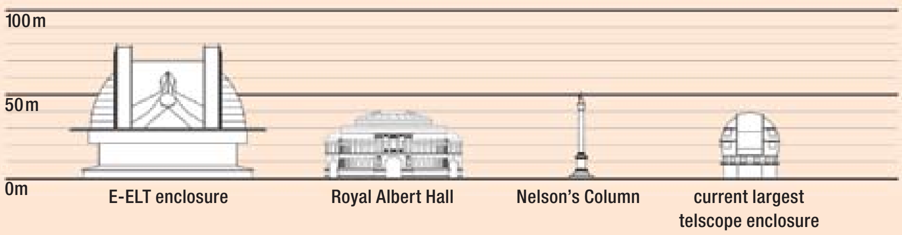
A novel feature of the telescope is its optical design, which comprises an on-axis, three-mirror anastigmat, with two exit mirrors ("M4" and "M5") used for correction of atmospheric turbulence and windshake. Thus, the E-ELT will be a fully *adaptive* telescope, delivering unprecedented sensitivity, combined with exceptional image quality. Fast tip and tilt motions will be corrected by M5, with higher-order terms corrected by M4. This will provide ground-layer AO correction, yielding significant performance gains at near-IR wavelengths and, potentially, into the red-optical region (e.g. Cunningham *et al*. 2008).

The primary mirror will be assembled from 984 segments, each of which will be actively controlled to maintain precise alignment at all times. The mirror segments will be drawn from several families to provide good tessellation at different radii. To allow for constant maintenance and re-aluminizing, this design needs a total of 1148 segments. Production of the segments will be one of the big challenges of the construction phase and industrial contracts for prototypes are already in place.

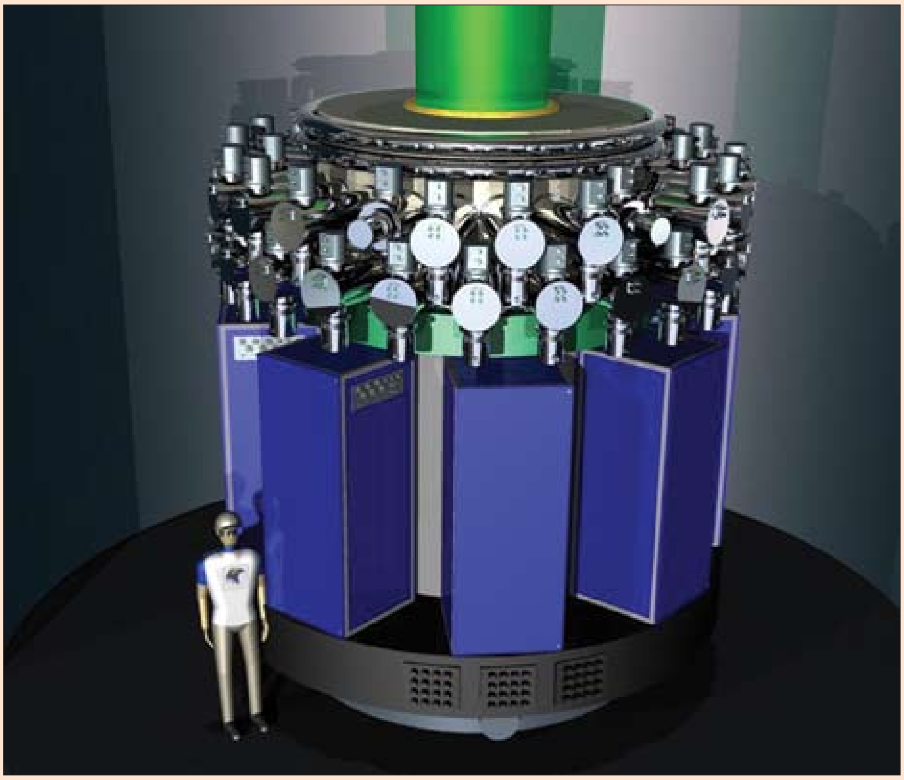
Construction of the facility could potentially start in 2010, with a total budget of around €900 million and an aggressive timescale aiming for first science around 2017. Potential sites include northern Chile, a high-altitude site in Argentina, Morocco and Spain (the Canary Islands). Obviously, a big consideration on the choice of the site will be the infrastructure required to access and maintain such a facility – for instance, the expected power requirements are likely to be of the order of 10 MW (compared to 6 MW for ESO's Paranal site). Work is continuing on studies of the mechanical support for the telescope, analysis of earthquake and wind tolerances, and the design of the enclosure – figure 2 demonstrates the truly impressive scale of the project!

An important aspect of the telescope design is the provision of large Nasmyth platforms for the instruments. This offers the potential for multiple foci at each of the two platforms, with large adaptors at the interface to the instruments to handle the laser and natural guide stars required for AO operations. One (or perhaps both) of the platforms feature a novel Gravity Invariant (GI) focus, in which the incoming light is directed by a large flat mirror (M6) to a room below. This provides the advantage of an instrument focal-plane that is parallel to the ground, compared to a traditional on-axis Nasmyth focus in which an instrument experiences a variable gravity vector as it rotates to compensate for field rotation. The telescope will also have a feed to a Coudé room providing an opportunity for very stable, ultra-high-resolution spectroscopy.

THE SCALE OF THE PROJECT



2: The E-ELT compared to two notable London landmarks. (ESO)



3: Early design of the EAGLE instrument – the engineer included for scale is 1.75 m tall. (UK ATC)

Phase A instrument studies

The objective of the UK programme has been to ensure a leading role in building the first and subsequent generations of E-ELT instruments, thereby ensuring that UK teams make early scientific breakthroughs from guaranteed time and detailed knowledge of the instruments. At the time of the RAS meeting there were six Phase A studies underway:

- CODEX: An ultra-high-resolution, high-stability optical spectrograph
- EAGLE: A multi-IFU, AO-corrected, near-IR spectrometer
- EPICS: Extreme-AO imager and spectro-polarimeter for exoplanet studies
- HARMONI: A single-field, wide-band, integral-field spectrograph
- MICADO: Near-IR, high-resolution imaging camera
- METIS: Thermal-IR imager and spectrometer.

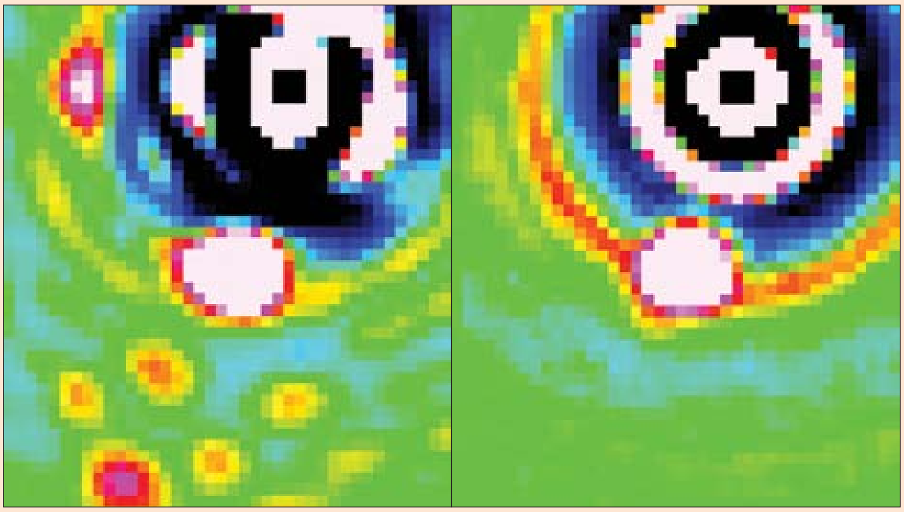
The UK is in a very strong position at this point: it is the lead partner on the HARMONI study, a 50% partner with France on the EAGLE study, is a minor partner in the METIS and EPICS studies, and UK astronomers are involved in the CODEX science team. The UK is also a major partner in the CANARY AO-pathfinder experiment. A key element of the RAS meeting was talks on the different components of the instrumentation programme, which are summarized below.

Oxford University is leading the HARMONI study for a single-field, wide-band spectrometer. Envisaged as a potential first-light instrument for the telescope, it is motivated by spectroscopic follow-up of faint sources discovered in deep imaging surveys (e.g. from the James Webb Space Telescope, JWST) that are completely out of reach of existing facilities. The science drivers call for high angular-resolution spectroscopy, spanning a range of targets from planetary science, stellar populations and high-redshift galaxies. HARMONI will be a near-diffraction-limited, integral-field unit (IFU) spectrometer with a field-of-view of 1″ to 5″, operating over the wavelength range of 1–2.5 μm, at a spectral resolution of $R \sim 4000$ (sufficient to enable good subtraction of the OH sky-line emission). Higher spectral-resolution modes and increased spectral coverage bluewards of 1 μm (both strongly motivated by studies of resolved stellar populations) are also under consideration.

The EAGLE consortium is a 50:50 partnership between the UK (via Durham University and the UK ATC) and France. Its science case comprises spatially resolved spectroscopy of targets ranging from heavily obscured, galactic star clusters, right out to the first galaxies at the highest redshifts. Whereas HARMONI is aimed at resolving the finest details of selected targets, EAGLE is motivated by the desire to obtain near-IR spectroscopy of many objects (across a ~5′ field) to build up representative and unbiased samples of, for example, hundreds of high-redshift galaxies. In this context, its science case calls for improved angular-resolution (~75–100 milliarcseconds) but not diffraction-limited performance, with a wavelength range of 0.8–2.5 μm (thus including the calcium triplet). Two spectral modes are planned: $R \sim 4000$ and $R \sim 10\,000$, with the latter for studies of radial velocities/metallicities in stellar populations and stellar clusters. The working assumption in the Phase A study is that EAGLE will be mounted at the GI Nasmyth focus mentioned previously. To illustrate the probable size of an instrument such as EAGLE, an early-stage design is shown in figure 3 – as the telescopes get bigger, so too do the instruments.

CANARY is the E-ELT pathfinder experiment

4: The Rayleigh laser guide star on the William Herschel Telescope. This is undergoing modification for use in the CANARY AO-pathfinder experiment. (ING)



5: VLT-SINFONI observations of AB Doradus A & C, before (left) and after (right) spectral deconvolution to remove the contribution of PSF "speckles" (Thatte *et al.* 2007). This is one technique under investigation for E-ELT studies of exoplanets.

for laser guide star (LGS), multi-object adaptive optics (MOAO) on the 4.2 m William Herschel Telescope (WHT). CANARY will also serve as an on-sky demonstrator for EAGLE. The EAGLE field-of-view (~5′ across) is too large an area to contemplate correcting for atmospheric turbulence with existing methods such as multi-conjugate AO – indeed, EAGLE does not require correction of every point in the field, merely "islands of correction" for each object. MOAO employs multiple LGS to map the turbulent layers above the telescope, driving deformable-mirrors in each channel of the instrument to correct for the turbulence in that part of the field.

As well as demonstrating MOAO in the EAGLE configuration, CANARY will improve real-time control and calibration methods that will be crucial to obtain the best performance from the E-ELT. CANARY will employ the Rayleigh LGS on the WHT (figure 4) to emulate the potential problems of using multiple sodium lasers on larger telescopes – the scenarios scale very neatly as the Rayleigh LGS on the 4.2 m WHT can work at an altitude of 8.5 km, whereas the sodium LGS on the 42 m E-ELT will work at 85 km.

The UK ATC is a minor partner of the Dutch-led METIS study for a mid-IR imager and spectrometer. Its science case covers topics such as exoplanets, protoplanetary discs, the formation of massive stars, the growth of supermassive black holes and the formation of dust-obscured, massive elliptical galaxies. The baseline design is for a diffraction-limited, high-contrast imager, combined with a high-resolution (up to $R \sim 100\,000$) IFU spectrometer, operating over the L, M and N bands (~3–13.5 μm). Options such as provision for polarimetry and extension to the Q band (depending, in part, on the site selected for the E-ELT) are being explored in the Phase A study. There will be a strong synergy between the capabilities of METIS and the JWST Mid-IR Instrument (MIRI) – the point-source sensitivities from MIRI will be hard to beat from the ground (even with a 42 m primary) but METIS will have significantly better angular-resolution, combined with high spectral-resolution. The UK ATC will be working on the spectrometer pre-optics to the IFU, exploiting previous investment in a similar module for MIRI.

EPICS is the study of a dedicated E-ELT instrument for the direct detection of exoplanets via imaging and spectroscopy (thereby complementing the CODEX science case, part of which is concerned with the indirect detection of planetary systems via their radial velocity shifts). The absolute best performance from the telescope will be needed to deliver contrast-ratios in the range of 10^{-7} to 10^{-9} for detection of very faint planets around their parent stars, entering the regime of "extreme AO" over very small fields. Even with the best possible AO correction, light that is not within the diffraction-limited core, e.g. from mis-alignment of the optical path, can interfere to produce "speckles" that may appear as real objects at a given wavelength, reducing the effective contrast. The University of Oxford has a key role in the development of the EPICS-IFU to counter this problem. It plans to employ the spectral deconvolution method (as demonstrated with VLT-SINFONI by Thatte *et al.* 2007; see figure 5) which subtracts the contaminating light from the star and from speckles.

Summary

The past two years have witnessed a tremendous amount of work toward the E-ELT, with the project advancing rapidly to tangible activities such as industrial prototyping, site monitoring, on-sky AO experiments and planning of a detailed construction schedule. The ESO member states (via ESO Council) have identified the E-ELT as the highest-priority project after completion of ALMA. Planning a decade and more into the future may seem remote at present but, as ground-based facilities become more ambitious, the lead-in time for projects are increasingly similar to those of space missions. To ensure the maximum return in the long term for UK astronomers and industry, we are continuing to participate in all aspects of the project over the next three years, particularly ahead of decisions regarding the construction phase, awarding of industrial hardware contracts and convergence to a final instrument suite. Once operational, the E-ELT will be the world's largest optical–infrared telescope, providing a unique facility from which UK astronomers will learn more about the universe and our place in it. ●

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