Prospects for studying resolved stellar populations with the E-ELT

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The E-ELT

- 40-m class telescope: largest optical-infrared telescope in the world
- Segmented primary mirror
- Active optics to maintain collimation and mirror figure
- Adaptive optics assisted telescope
- Diffraction limited performance
- Wide field of view: 10 arcmin
- Mid-latitude site (Armazones in Chile)
- Fast instrument changes
- VLT level of efficiency in operations
Current status in a nutshell

• Top priority of European ground-based astronomy (on Astronet and ESFRI lists).
• Project (led by ESO) completed its detailed design phase (Dec 2006 - Dec 2010), with a total budget of 62 M€ from ESO + 35 M€ from EC Framework Programmes (FP6/FP7).
• Final Design Review passed in Sep 2010.
• 8 instrument + 2 AO module concept studies completed.
• Site selected: Cerro Armazones in Chile.
• Recent development (Jun 2011): change of baseline design.
• Construction planned to begin in 2012.
• Start of operations early next decade.
• Construction cost: ~1 B€ (incl first-light instrumentation).
Most recent developments

- In June 2011 ESO Council endorsed a revised baseline design for the E-ELT.
- The overall concept of the original design remains unchanged.
- Main changes:
  - Reduction of primary mirror diameter by removing two rings of segments:
    | Largest fully enclosed D | Circumscribing D | Area      | Segments |
    |--------------------------|-----------------|-----------|----------|
    | Original 42-m design:    | 41.3 m          | 43.2 m    | 1212 m²  | 984      |
    | New design:              | 37.0 m          | 39.3 m    | 978 m²   | 798      |
  - Faster f-ratio.
  - Loss of gravity invariant focal station.
- Instrumentation plans and budget remain unchanged.
The Telescope

- Nasmyth telescope with a segmented primary mirror.
- Novel 5 mirror design to include adaptive optics in the telescope.
- Classical 3-mirror anastigmat + 2 flat fold mirrors (M4, M5).

- Two instrument platforms nearly the size of tennis courts can host 3 instruments each + Coudé lab.
- Six laser guide stars (provisions for eight), launched from the side.
- Nearly 3000 tonnes of moving structure.

![Telescope Diagram](image)

Spot diagram:

- 50 mas
- On axis: 2 arcmin
- Distance from FoV centre
The Mirrors

M1: 39.3 m, 798 hexagonal segments of 1.45 m tip-to-tip: 978 m$^2$ collecting area

M4: 2.4 m, flat, adaptive
6000 to 8000 actuators

M5: 2.6 x 2.1 m, flat,
provides tip-tilt correction
The Dome

- Rather classical design.
- Diameter = 86 m, height = 74 m.
- ~3000 tonnes of steel.
- Fully air-conditioned and wind shielded.
In principle, the telescope can host up to 8 instruments: 3 on each Nasmyth platform, 2 in the Coudé lab.
Instrument and AO modules Study Plan (April 2007):

• **Goal:** definition of a first generation instrument set to be included in the E-ELT construction proposal.

• **Scope:**
  - Carry out a suitable number of instrument studies to verify that instruments can be built at an affordable cost and that they properly address the scientific goals of highest priority.
  - Work with the ESO community in studying 8 instruments + 2 AO modules and to prepare for construction.
  - Work with telescope and operation POs to identify and define interfaces with the other subsystems and the observatory infrastructure.

• **Budget:** 2.3 M€ (2007-2010).
Instrumentation

- 8 instrument concept (phase A) studies
- 2 post-focal adaptive optics module studies

Scope
- Detail the science case.
- Finalize the instrument requirements.
- Develop an instrument concept including cost and construction schedule.

- All phase A studies were successfully completed by early 2010.
## Phase A studies

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODEX</td>
<td>High-resolution, high-stability optical spectrograph</td>
</tr>
<tr>
<td>EAGLE</td>
<td>Wide-field NIR multi-IFU</td>
</tr>
<tr>
<td>EPICS</td>
<td>Extreme AO planet imager and spectrograph</td>
</tr>
<tr>
<td>HARMONI</td>
<td>Single field NIR wide-band IFU</td>
</tr>
<tr>
<td>METIS</td>
<td>MIR imager and spectrograph</td>
</tr>
<tr>
<td>MICADO</td>
<td>Diffraction limited NIR imager</td>
</tr>
<tr>
<td>OPTIMOS</td>
<td>Wide-field optical MOS</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>High-resolution NIR spectrograph</td>
</tr>
<tr>
<td>ATLAS</td>
<td>Laser Tomography AO module</td>
</tr>
<tr>
<td>MAORY</td>
<td>Multi Conjugate AO module</td>
</tr>
</tbody>
</table>
Parameter space covered by phase A studies
Current plan:

- Following recommendations by the SWG and STC, 2 first-light instruments have been identified.
- All phase A studies remain in the pool of possible instruments.
- Thereafter start a new instrument every 2 years.
The Site

Following an extensive site testing campaign, involving several sites in Chile, Morocco, the Canary Islands, Argentina, Mexico, ... , ESO Council selected Cerro Armazones as the E-ELT site.

Selection criteria: impact on science, outstanding atmosphere, but also construction and operations logistics (roads, water, electricity, nearby cities, ...).
The Site

Armazones

Paranal
Looking ahead

- Dec 2011: Go-ahead for construction from ESO Council
- And then...

2012 2013 2014

2015 2016
Looking ahead

- Dec 2011: Go-ahead for construction from ESO Council
- And then...
ELT comparison

<table>
<thead>
<tr>
<th></th>
<th>GMT</th>
<th>TMT</th>
<th>E-ELT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter:</td>
<td>25.4 m</td>
<td>30 m</td>
<td>39.3 m</td>
</tr>
<tr>
<td>Collecting area:</td>
<td>382 m²</td>
<td>655 m²</td>
<td>978 m²</td>
</tr>
<tr>
<td>Diff. limit at 1µm:</td>
<td>9.9 mas</td>
<td>8.4 mas</td>
<td>6.4 mas</td>
</tr>
</tbody>
</table>
Stellar archaeology

- Present day population of stars in a galaxy = result of all of the star-formation it (or its precursors) experienced + stellar evolution.
- We understand stellar evolution.
  ➔ A galaxy's present-day stellar population can be used to deduce the galaxy's major episodes of star-formation and hence to reconstruct its assembly history.
- Stars retain a memory of the ISM out of which they formed. Some stars are very long-lived → handy tracer of star-formation conditions from the earliest times to the present.
Resolved stellar populations $\Rightarrow$ galaxy evolution

- Want to obtain precise photometry and spectroscopy of resolved stellar pops for a wide range of stellar systems:
Resolved stellar populations \(\rightarrow\) galaxy evolution

- Want to obtain precise photometry and spectroscopy of resolved stellar pops for a wide range of stellar systems:
Virgo CMDs with HST

V ~ 27.5 mag/arcsec²

Caldwell (2006)

Durrell et al. (2007)
Virgo CMDs with HST

Caldwell (2006)

Durrell et al. (2007)

181 stars
Virgo
CMDs with HST

Inner region of M87
Virgo CMDs with HST

Bird et al. (2010):
- HST/ACS
- 12.5” x 12.5”
- F814W
- ~20 hours
- 0.025”/pixel
Virgo
CMDs with HST

Bird et al. (2010):
• HST/ACS
• F814W
• ~20 hours
• 0.025"/pixel
Virgo CMDs with HST

Bird et al. (2010):
• HST/ACS
• 3" x 3"
• F814W
• ~20 hours
• 0.025"/pixel
Simulation:
I-band
10 hours
3'' x 3''
DM = 31.2
μ = 23 mag/arcsec²

TinyTim model of
HST ACS  F814W
PSF from Rhodes et al. (2007),
no drizzling
Simulation:
I-band
10 hours
3'' x 3''
DM = 31.2
\( \mu = 23 \text{ mag/arcsec}^2 \)

E-ELT I-band PSF
Simulation:
I-band
10 hours
3'' x 3''
DM = 31.2
$\mu = 23 \text{ mag/arcsec}^2$

E-ELT I-band PSF
Simulation:
I-band
10 hours
0.8" x 0.8"
DM = 31.2
\( \mu = 23 \text{ mag/arcsec}^2 \)

E-ELT I-band PSF
Resolved stellar populations and the E-ELT

• Very prominent science case for the E-ELT!
Resolved stellar populations and the E-ELT

- Very prominent science case for the E-ELT!

Quick look: what can we expect?

Isochrones:
- $[\text{Fe/H}] = -1.8, -1, -0.6$
- Age = 5, 9, 13 Gyr

Mag limits:
- $T_{\text{exp}} = 10$ hours
- $S/N = 20$
- No crowding
Resolved stellar populations and the E-ELT

• Very prominent science case for the E-ELT!

• Selected by the E-ELT Science Working Group for study by the Design Reference Mission (DRM).

• DRM = hands-on exploration of a few science cases through the analysis of simulated E-ELT data. Purpose:
  - quantitative assessment of what the E-ELT will be able to achieve
  - assist in trade-off decisions
  - support development of Science Case

• See http://www.eso.org/sci/facilities/eelt/science/drm/

• Two RSP cases considered in the DRM:
  - Imaging: CMDs of elliptical galaxies
  - Spectroscopy (G. Battaglia)
  - SWG member responsible: Eline Tolstoy
E-ELT and CMDs: specific questions

- What is the limiting magnitude down to which accurate photometry of a galaxy's RSP is possible as a function of:
  - the galaxy's distance
  - the surface brightness within the galaxy (equivalent to galactocentric radius for a given profile)
  - the observing band (what is the best combination of bands to use?)
  - the performance of the AO
  - the assumed stellar population

- What is the effect of PSF uncertainties?

- Method: brute-force Monte Carlo simulations
Stellar population

BaSTI isochrones Cordier et al. (2007)

SFH IMF chemical comp. $\alpha$ enhancement

Input catalogue

observational parameters: telescope, PSF, etc.

distance surface brightness spatial distribution

Matched catalogue

StarFinder

Output catalogue

Photometry assessment

Measured CMD
Simulation parameters

- Stellar population:
  - SFH: constant from 14 – 12 Gyr ago
  - IMF: Salpeter, i.e. $\alpha = -2.35$
  - $[\text{Fe/H}] = -1.8, -1, -0.6$

- Galaxy data:

<table>
<thead>
<tr>
<th></th>
<th>NGC 205 (LG)</th>
<th>Cen A (NGC 5128)</th>
<th>M87</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM</td>
<td>24.58</td>
<td>27.92</td>
<td>31.2</td>
</tr>
<tr>
<td>kpc/arcsec</td>
<td>0.00396</td>
<td>0.0186</td>
<td>0.084</td>
</tr>
<tr>
<td>kpc/arcmin</td>
<td>0.238</td>
<td>1.116</td>
<td>5.055</td>
</tr>
<tr>
<td>Profile</td>
<td>Exponential</td>
<td>de Vaucouleurs</td>
<td>de Vaucouleurs</td>
</tr>
<tr>
<td>Scale or effective radius (arcsec)</td>
<td>$h = 102$</td>
<td>$R_e = 330$</td>
<td>$R_e = 105$</td>
</tr>
<tr>
<td>Central or effective SB (mag arcsec$^{-2}$)</td>
<td>$\mu_0 = 20.4$</td>
<td>$\mu_e = 22.15$</td>
<td>$\mu_e = 20.58$</td>
</tr>
</tbody>
</table>

- Telescope: 42 m!

- PSFs: ESO's in-house simulations of LTAO PSFs.
LTAO PSFs

• Because ESO's PSF simulations are computationally so expensive only short integration PSFs (4s) have been simulated.

• Problem: speckle noise.

• Also: the PSF images have to be very large in order to sample a good contrast range.

• Solution: represent PSFs with a 'small' number of analytic components.
PSF fitting
PSF fitting

H

K
Simple test case: no crowding
Full result: M87
Full result: M87

\[ \sigma_J = 0.05 \text{ mag} \]

\[ \sigma_J = 0.1 \text{ mag} \]

Crowding limited

Background limited

\( T_{\text{exp}} = 100 \text{ h} \)
Full result: M87

Crowding limited

Background limited
($T_{\text{exp}} = 10 \text{ h}$)
Full result: M87

\[ \sigma_J = 0.05 \text{ mag} \]

\[ \sigma_J = 0.1 \text{ mag} \]
Full result: M87

\[ \sigma_J = 0.05 \text{ mag} \]

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Full result: M87
M87
Cen A
NGC 205
Effect of resolution

Original: $D = 42$ m
Effect of resolution

D = 60 m
Effect of resolution

$D = 42 \text{ m}$
Effect of resolution

$D = 30\,\text{m}$
Effect of AO performance

Original: intermediate Strehl
Effect of AO performance

The diagram shows the effect of adaptive optics (AO) performance on the Strehl ratio, a measure of image quality. The Strehl ratio is indicated by the color scale, with higher values representing better image quality. The graph plots the Strehl ratio against spatial frequency (μν in mag arcsec⁻²) and contrast level (J in mag). The region labeled 'high Strehl' indicates areas of high image quality.
Effect of AO performance

intermediate Strehl
Effect of AO performance

The graph shows the effect of AO performance on the J-band PSF for different Strehl ratios. The color scale represents the log of the J-band Strehl ratio, with darker colors indicating lower Strehl ratios. The data points and curves indicate the change in the PSF with respect to the J-band magnitude and angular resolution.
AO performance

The graphs show the relationship between the logarithm of the signal-to-noise ratio (Log S/N) and the logarithm of the size of the S/N reference area (Log(size of S/N reference area [mas])). The plots are categorized by different magnitudes and include markers indicating ETC: $I_c = 25$ mag, $I_c = 26$ mag, $I_c = 27$ mag, and ETC: $I_c = 27$ mag, no AO.

- The top left graph demonstrates the effect of varying magnitudes on the Log S/N for $I_c$ values.
- The top right graph compares the same effect for different magnitudes in the $I$ band.
- The bottom left graph illustrates the impact on Log S/N for varying $J$ magnitudes.
- The bottom right graph shows the Log S/N relationship for different $H$ magnitudes.

This analysis suggests that as the magnitude increases, the Log S/N decreases, indicating poorer performance with higher magnitudes for each band.
Effect of stellar population

Original: intermediate metallicity
Effect of stellar population

metal-rich
Effect of stellar population

metal-poor
Effect of PSF errors

Using different PSFs for the image generation and analysis.
Effect of PSF errors

Using different PSFs for the image generation and analysis.

5% PSF “perturbation”
Effect of PSF errors

Using different PSFs for the image generation and analysis.

10% PSF “perturbation
Effect of PSF errors

PSFs will vary as a function of:

• Position within the FoV
• Time
• Airmass
• Colour of the star
• ...

How will these variations be calibrated out?
Summary

- For M87 in the Virgo cluster the E-ELT will be able to probe the TRGB with 0.05 mag accuracy all the way into the very dense central parts of the galaxy, down to ~0.5 $R_e$.

- The accuracy of the photometry in crowded stellar fields is entirely driven by resolution. It is independent of the quality of the AO correction as long as the correction is good enough to provide a reasonably well-developed diffraction-limited core in the PSF. Beyond this requirement the value of the Strehl ratio is immaterial.

- Given current AO predictions the above point will restrict RSP studies with the E-ELT to wavelengths > 0.9 µm.

- PSF variations will have to be tracked at a level of a few %.
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