

# Massive stars in the era of ELTs

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**Abstract:** Plans for the next generation of optical-infrared telescopes, the Extremely Large Telescopes (ELTs), are well advanced. With primary apertures in excess of 20 m, they will revolutionise our ground-based capabilities. In this review I summarise the three current ELT projects, their instrumentation plans, and discuss their science case and potential performance in the context of studies of massive stars.

## 1 Introduction

In many fields of astronomical research we have already approached the sensitivity limits of the 8-10 m class telescopes. Improvements in performance such as better instrument throughputs and further developments in adaptive optics (AO) will likely come in the next few years, but we are fundamentally limited by the collecting areas and (potential) diffraction limits of existing facilities.

The primary motivation to embark on plans for the next generation of ground-based optical and near-IR facilities, the Extremely Large Telescopes (ELTs), is the huge gain from the combination of sensitivity and angular resolution. Large primary apertures will collect more photons from each target and, with correction of atmospheric turbulence via AO, we will achieve angular resolutions beyond our current capabilities (excluding those targets which are bright enough for optical-IR interferometry). The science case for the ELTs is typically split into three areas:

- *Planets & Stars:* including detection and characterization of extra-solar planets, and a broad range of topics relating to solar system science, proto-planetary discs and star formation.
- *Star & Galaxies:* bridging ‘local’ topics such as the formation and evolution of stellar clusters, out to using stellar populations to study the assembly histories of galaxies beyond the Local Group and, to even larger distances, the study of black holes in active galactic nuclei.
- *Galaxies & Cosmology:* ranging from studies of galaxy evolution at low redshifts, out to characterization of the highest redshift (‘first light’) systems and studies of cosmic expansion.

Some of the cases relating to ELT studies of massive stars are now discussed, together with a brief consideration of the broader astronomical landscape in the 2020s. Section 2 gives an overview of the three current ELT projects, while Section 3 gives example performances and highlights the need to improve near-IR diagnostics to exploit the ELTs to their best potential. Lastly, Section 4 summarises recent observations with a successful AO pathfinder on the Very Large Telescope (VLT), as an example of the power of ‘wide field’ AO techniques.

## 1.1 Star formation

The main thrust of this review is related to extra-galactic studies but it is worth noting the likely contribution of the ELTs toward our understanding of star formation. The tremendous gain here will be the combination of angular resolution with the ability to penetrate the significant optical extinction (typically tens to over a hundred magnitudes) toward ultra-compact H II regions by observing at near- and mid-IR wavelengths (Zinnecker, 2006). Together with other new facilities such as the Atacama Large Millimetre Array (ALMA), we will truly have a multi-wavelength suite of tools to probe the processes at work in the formation of massive stars.

The potential of modern techniques in this area is neatly illustrated by recent observations of W33A by Davies et al. (2010). This is a well-studied massive young stellar object in the Galaxy, at a distance of nearly 4 kpc and with significant extinction at optical wavelengths. Using AO-corrected, *K*-band observations with the Gemini Near-IR Integral Field Spectrograph (NIFS), Davies et al. were able to investigate the different spatial structures related to W33A. Supported by interferometric results from de Wit et al. (2007, 2010), they conclude that the star is forming via similar processes to those seen in lower mass objects, i.e., accretion from a circumstellar disc, while driving a bi-polar outflow. The collapsed *K*-band NIFS image is shown in the left-hand panel of Fig. 1, with spectra of selected regions shown in the right-hand panel; note the spatial scales of  $\sim 0''.1$  in the NIFS image.

With much greater sensitivity, the ELTs will be able to extend studies of ultra-compact H II regions and young stellar objects/clusters to much larger distances and to systems with greater extinction. In this area there will be strong complementarity between the scales probed by the ELTs and by interferometry with, e.g. the Very Large Telescope Interferometer (VLTI). Indeed, the power of VLTI is highlighted by the recent detection of a dusty disc around another very young massive star, IRAS 13481–6124 (Kraus et al. 2010).

Although we are starting to glean some of the first views of the formation of individual massive stars, the majority appear to be in binary/multiple systems (e.g., Mason et al. 2009; Sana & Evans, 2011). The dominant formation mechanism of such systems is still not clear (e.g. Gies, 2008) and, if we want to be able to understand the integrated light populations of distant star-forming galaxies (which are dominated by massive stars), it is clear we still have much to learn.

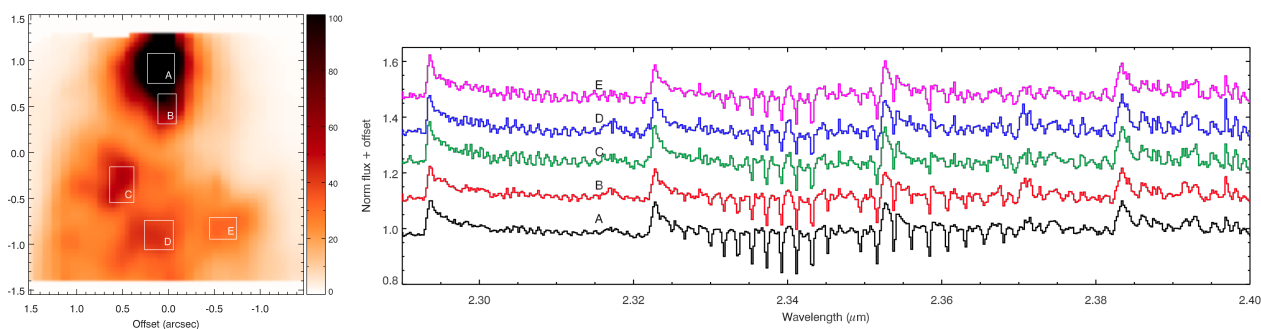


Figure 1: *Left*: Gemini-NIFS *K*-band image of W33A from Davies et al. (2010). *Right*: *K*-band spectra of the bright central source (region ‘A’) and other knots of emission (‘B’ to ‘E’). The variations in the CO spectra were used by Davies et al. to constrain the geometry of material around W33A.

## 1.2 Stellar spectroscopy beyond the Local Group

One of the big impacts of the 8-10 m telescopes compared to previous facilities has been to obtain high-quality stellar spectroscopy in external galaxies. For example, this gain in sensitivity is evident

for targets in M31, where new Gemini-GMOS spectroscopy of luminous supergiants (Cordiner et al. 2011) makes light work of observations which were challenging with 4 m telescopes (e.g. Bianchi et al. 1994; Herrero et al. 1994). There are two observational regimes in the current 8-10 m era:

- *Fundamental stellar astrophysics in nearby galaxies:* High-quality spectroscopy for quantitative analysis of individual massive stars in the Magellanic Clouds was only possible for selected bright targets with 4 m telescopes. With the advent of multi-object instruments such as FLAMES on the VLT we have been able to obtain large spectroscopic samples of the massive star populations of the Clouds (and the Milky Way) to investigate the role of environment on stellar properties and evolution (e.g. Evans et al. 2005a, 2005b; Martayan et al. 2006, 2007).
- *Stars as tracers of galaxy properties:* Beyond 1 Mpc, we have had our first glimpses of spectra of individual stars in galaxies such as NGC 3109 (Evans et al. 2007) at 1.3 Mpc, and NGC 300 (Bresolin et al. 2002) and NGC 55 (Castro et al. 2008), both of which are spiral galaxies in the Sculptor ‘Group’ at  $\sim 1.9$  Mpc (Pietrzyński et al. 2006). Such data can be used to estimate the present-day abundances in these galaxies, to study radial abundance trends in the spirals (Urbaneja et al. 2005), and to help refine our understanding of other diagnostics used in interpretation of more distant systems (Bresolin et al. 2009). The most impressive observations in this context are the VLT spectra of two supergiants in NGC 3621 (Bresolin et al. 2001), at a remarkable distance of 6.7 Mpc.

The arrival of the ELTs will represent an even greater leap forward in our capabilities than that when moving from 4 to 8 m, opening-up an exciting range of options for future study, including:

- *Physics & evolution of massive stars in metal-poor irregulars:* Quantitative analysis of blue supergiants in galaxies such as IC 1613, WLM and NGC 3109 has found oxygen abundances slightly below those found in the Small Magellanic Cloud (Bresolin et al., 2006, 2007; Evans et al. 2007). Determining exact metallicities requires further work, but it is clear that these systems provide an excellent opportunity to expand our studies of massive stars in metal-poor regimes – from the most extreme, luminous phases to main-sequence dwarfs.
- *Massive star populations of nearby spirals:* The full luminosity range of massive stars will also be accessible in local spirals. This includes galaxies such as NGC 55 and NGC 300, but the real prize here is the potential of studying the full age-range of populations in both M31 and M33 – from main-sequence massive stars to the oldest evolved red giants. There is already significant deep imaging in these galaxies, and a new multi-cycle *HST* Treasury Program to image one quadrant of M31 at UV/optical/near-IR wavelengths (‘A Panchromatic Hubble Andromeda Survey; PI: J. Dalcanton) will provide rich sources of exciting objects worthy of ELT spectroscopy for quantitative abundances and radial velocities.
- *The most luminous stars in distant galaxies:* As we move beyond the Local Group, there is a rich assortment of galaxy types and environments/groups. Here we can seek to use our understanding of massive stars to learn about the host galaxies. For example, in the starburst galaxy M82, in ellipticals such as Cen A (NGC 5128), NGC 3379 and members of the Virgo Cluster, and in interacting systems such as M51. Looking even further afield, we can exploit the angular resolution of the ELTs to resolve the cluster complexes in the Antennae into their sub-components to assess their ages/populations. Perhaps one of the most compelling targets for further study in terms of its apparently *very* metal-poor population is I Zw 18 (Heap et al. 2011), at a distance 18.2 Mpc (Aloisi et al. 2007). As noted by others in the literature, I Zw 18 could provide important insights into stellar evolution in conditions which are more in keeping with those in the very early universe.

### **1.3 Synergies with other facilities**

The current generation of ground-based, optical-IR telescopes will continue to deliver exciting new results over the coming decade, particularly with the arrival of new instrumentation. However, deep imaging from the 8-10 m telescopes and the *Hubble Space Telescope (HST)* is already revealing targets which are beyond our spectroscopic capabilities. The need for follow-up will become increasingly important, not to mention the potential of combining, e.g, VLTI observations with ELT integral-field spectroscopy.

Such synergies will become even more crucial when looking ahead to ALMA and the *James Webb Space Telescope (JWST)*, both of which will start operations in the coming few years. They will be unique at their respective wavelengths, but supporting ground-based, optical-IR observations will be critical, as exemplified by years of *HST* operations.

Looking further ahead, the impact of other facilities such as the Large Synoptic Survey Telescope (LSST), the Square Kilometre Array (SKA), and the *International X-ray Observatory (IXO)*; (Rauw & Oskinova 2011) would all benefit hugely from the ability to obtain, e.g., spectroscopic follow-up or diffraction-limited imaging with an ELT.

### **1.4 Anticipating the unknown**

There are a wide range of scientific motivations for the ELTs, all informed by our current research and contemporary understanding; it is harder to plan for the unknown discoveries which await in the coming decade. Harwit (1981) made the point that new discoveries are generally achieved when a new part of parameter space is accessed for the first time. An excellent example of this is provided by the first sub-millimetre observations of distant galaxies (e.g. Smail, Ivison & Blain, 1997). The ELTs will excel in the combination of collecting power and angular resolution so, while we should design the observatories and their instruments to provide the best possible performance for the observations we can contemplate now, we should be wary of focussing those capabilities too much, rendering us unable to investigate future discoveries that we can not even conceive of today.

## **2 ELTs: Worldwide context**

Efforts toward building ELTs are becoming increasingly global, with three projects now in the advanced stages of their design, fund-raising and planning; the top-level details of each observatory are summarised briefly below. While these projects are collectively referred to as ‘ELTs’, note that there is a large range in the effective areas of their primary apertures.

### **2.1 GMT: The Giant Magellan Telescope<sup>1</sup>**

The GMT employs seven monolithic 8 m mirrors to form the primary aperture. Six of these are off-axis, arranged around the central on-axis mirror (see left-hand panel of Fig. 2). The effective diameter in terms of potential angular resolution is 24.5 m, with an equivalent collecting area of a  $\sim 22$  m filled-aperture primary. At the time of writing, GMT includes ten partners. These are primarily in the United States, but also include members in South Korea and Australia. The intended GMT site is at the Las Campanas Observatory in Chile, already home to the Magellan, Du Pont and Swope telescopes.

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<sup>1</sup><http://www.gmto.org>

## 2.2 TMT: The Thirty Meter Telescope<sup>2</sup>

The initial partners of TMT were Caltech, University of California and Canada. Over the past couple of years this partnership has expanded to include Japan, China and, most recently, India. The effective diameter of the primary is 30 m, comprised of hexagonal segments which are just over 1.4m in diameter (across the corners). This design builds on the considerable experience of the segmented primaries of the Keck telescopes. The TMT will be located on Mauna Kea in Hawaii, with a novel ‘Calotte’ dome to minimise wind shake (and cost), as shown in the right-hand panel of Fig. 2. An integral part of the project has been to minimise the environmental impact of the observatory on the mountain, including an updated design of the dome and the offices (beyond the one shown in Fig. 2).



Figure 2: *Left:* The GMT in its enclosure (image credit: Giant Magellan Telescope – GMTO Corporation); *Right:* Artist’s interpretation of the TMT on Mauna Kea, Hawaii (credit: the Thirty Meter Telescope Project).

## 2.3 E-ELT: The European Extremely Large Telescope<sup>3</sup>

The E-ELT is under development by the European Southern Observatory (ESO) on behalf of its partners, and features a primary with an equivalent diameter of 42 m (Fig. 3). As with the TMT, the primary is comprised of 1.4 m hexagonal segments. In addition to the primary, secondary and tertiary elements, the telescope design features an adaptive fourth mirror and a fast tip-tilt fifth mirror. The E-ELT site was announced earlier in 2010 to be Cerro Armazones in northern Chile. This is approximately 20 km from Paranal (the site of the VLT), meaning that some of the infrastructure and operations costs can be shared. Armazones is at an altitude of 3060 m, slightly higher than Paranal.

## 2.4 Instrumentation plans

Detailed overviews of the instrumentation studies completed or underway for each of the three ELT projects were given at the recent SPIE meeting in San Diego (GMT: Jaffe et al. 2010; TMT: Simard et al. 2010; E-ELT: Ramsay et al. 2010). A vast range of parameter space is covered by these studies. This is, in part, to be able to evaluate the relative merits of different capabilities toward each science case, but also to explore the technology readiness/requirements of key components for the future.

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<sup>2</sup><http://www.tmt.org>

<sup>3</sup><http://www.eso.org/sci/facilities/eelt>

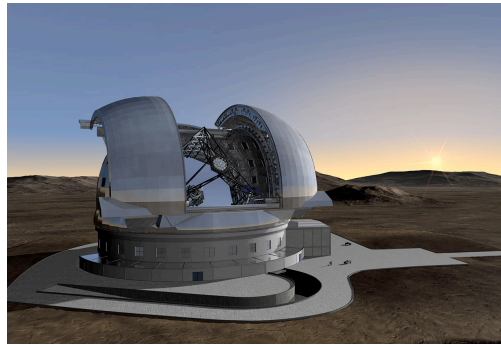


Figure 3: Recent design of the E-ELT in its enclosure (Credit: ESO).

The instrument studies undertaken to date are given in Tables 1, 2, and 3. Part of the motivation for such a comprehensive list is not to dazzle or overwhelm with acronyms and abbreviations, but to illustrate the significant effort that has already gone into these projects from the instrumentation part of the community, in close collaboration with the astronomers who have developed the science cases, undertaken simulations etc.

The first round of studies for TMT were completed in 2008, with three instruments subsequently selected for ‘early light’ operations, as indicated in Table 2. A similar down-select will form part of the E-ELT construction proposal, to be released in late 2010. The GMT studies will end in July 2011, with a down-select following thereafter.

Table 1: GMT conceptual design studies (Jaffe et al. 2010).

| Instrument | Brief description   |
|------------|---|
| G-CLEF     | High resolving power, high stability, optical spectrograph                    |
| GMACS      | Multi-slit, seeing-limited, optical spectrograph                              |
| GMTIFS     | AO-corrected, integral field, near-IR spectrograph ( <i>à la</i> GEMINI-NIFS) |
| GMTNIRS    | AO-fed, high resolving power, near-IR spectrograph                            |
| NIRMOS     | Multi-slit, near-IR spectrograph  |
| TIGER      | Mid-IR imager and low-resolution spectrograph                                 |

Table 2: TMT capabilities for first decade (Simard et al. 2010).

| Instrument | Brief description  |
|------------|--|
| IRIS       | AO-fed, near-IR, integral field unit (IFU) and imager            |
| IRMS       | AO-fed, multi-slit, near-IR spectrograph (clone of Keck-MOSFIRE) |
| WFOS       | Seeing-limited, multi-object, optical spectrograph               |
| HROS       | High-resolving power, seeing-limited, optical spectrograph       |
| IRMOS      | Multi-IFU, AO-corrected, near-IR spectrograph                    |
| MIRES      | AO-fed, mid-IR, echelle spectrograph                             |
| NIRES      | AO-fed, near-IR, echelle spectrograph                            |
| PFI        | High contrast, near-IR imager                                    |
| WIRC       | ‘Wide field’, AO-corrected imager                                |

The first three instruments (IRIS, IRMS and WFOS) are those planned for ‘early light’.

Table 3: E-ELT Phase A studies (Ramsay et al. 2010).

| Instrument | Brief description   |
|------------|---|
| CODEX      | High resolving power, high stability, optical spectrograph  |
| EAGLE      | Multi-IFU, AO-corrected, near-IR spectrograph               |
| EPICS      | High contrast, near-IR imager/spectro-polarimeter           |
| HARMONI    | AO-fed, near-IR, IFU  |
| METIS      | AO-fed, mid-IR imager and spectrograph                      |
| MICADO     | Near-IR, diffraction-limited imager                         |
| OPTIMOS    | Seeing-limited/ground-layer AO, high-multiplex spectrograph |
| SIMPLE     | AO-fed, near-IR, high resolving power spectrograph          |

### 3 Illustrative performances

To illustrate the spectroscopic potential of ELTs, I refer to simulations from the EAGLE Phase A study for the E-ELT (Cuby et al. 2010). EAGLE is a conceptual design for an AO-corrected, near-IR spectrograph with multiple integral field units (IFUs). A key element of its science case is spectroscopy of resolved stellar populations beyond the Local Group, using evolved red giant stars to trace the star-formation histories of their host galaxies. Tools have been developed to simulate EAGLE observations (Puech et al. 2008, Puech, Yang, & Flores 2010), which employ a set of simulated, AO-corrected, point-spread functions (PSFs) for example configurations of natural guide stars (Rousset et al. 2010).

Simulated EAGLE performances for spectroscopy of the calcium triplet (centered at  $0.86 \mu\text{m}$ ) were given by Evans et al. (2010). The continuum signal-to-noise (S/N, per pixel) resulting from some of these simulations is summarised in Table 4 for two configurations of guide stars; other relevant parameters were a spectral resolving power,  $R$ , of 10000, a total exposure time of 10 hrs ( $20 \times 1800\text{s}$ ) and a seeing of  $0''.65$ . From a stacked 10 hr exposure at  $I = 24.5$  (in the Vega System), a continuum  $S/N \geq 10$  is recovered, some four magnitudes deeper than FLAMES-GIRAFFE on the VLT using the LR08 setting (which is also at a lower resolving power of  $R = 6500$ ), with the same exposure time.

Table 4: Continuum signal-to-noise (S/N, per pixel) obtained for simulated EAGLE observations of the calcium triplet (Evans et al. 2010), with  $R = 10000$ ,  $t_{\text{exp}} = 10$  hrs, and two configurations of natural guide stars (NGS).

| $I_{\text{VEGA}}$ | S/N          |              |
|-------------------|--------------|--------------|
|                   | [NGS 'Good'] | [NGS 'Poor'] |
| 22.5              | 56           | 48           |
| 23.5              | 28           | 24           |
| 24.5              | 13           | 10           |

These simulations were originally to quantify the performances for red giant stars, but we can also consider their implications in the context of massive stars, where we typically require a  $S/N \geq 50$ . The reach of  $I$ -band spectroscopy of different populations is summarised in Table 5. I know the  $I$ -band is not exactly replete with useful diagnostics in the spectra of massive stars (!), but these performances are merely to give a feel for the distances to which one can contemplate ELT observations. The bottom-line is that the ELTs will provide spectroscopy of individual stars beyond the Local Group, in the same manner that we have begun to take for granted in nearby galaxies.

#### 3.1 Future diagnostics

An important additional factor in performance calculations for ELTs is the level of AO correction. Seeing-limited spectroscopy in the optical (covering the diagnostic lines with which we have con-

Table 5: Distance moduli (DM) and distances ( $d$ ) to which  $I$ -band spectroscopy could be obtained with EAGLE (at  $R = 10000$  and given S/N), assuming the performances from Table 4.

| Star                    | S/N       | $M_I$ | DM   | $d$     |
|-------------------------|-----------|-------|------|---------|
| Tip of red giant branch | $\geq 10$ | -4    | 28.5 | 5 Mpc   |
| BA-type supergiants     | $\geq 50$ | -7    | 29.5 | 8 Mpc   |
| O-type dwarf            | $\geq 50$ | -4.5  | 27.0 | 2.5 Mpc |

siderable experience) could yield spectra of supergiants in the outer halos of distant galaxies, but to probe into the densest regions we will require the best possible contrast from AO, which will be limited to relatively small fields. Moreover, for stellar spectroscopy with the ELTs there will be a fine balance in sensitivity between the improved image quality from adaptive optics as one goes to longer wavelengths (where the wavefront errors become less significant compared to the observational wavelengths) versus the increased background. As an example of the wavelength dependence of the AO correction, Fig. 4 shows results for the encircled energy within a 75 milliarcsecond aperture from the simulated EAGLE PSFs (Rousset et al. 2010).

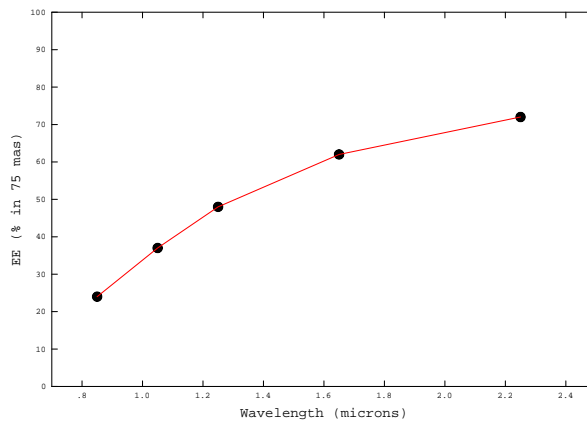


Figure 4: The wavelength dependence of the effective AO correction is shown by the encircled energy (EE) delivered in 75 milliarcseconds by the simulated EAGLE PSFs (Rousset et al. 2010).

Martins (2011) summarised the broad range of diagnostics available to us in our efforts to determine the physical parameters of massive stars. For example, in regions of high extinction such as the Galactic Centre,  $K$ -band spectroscopy provides the means to study stellar winds (Martins et al. 2007). Work is already underway to improve our understanding of near-IR diagnostics compared to those in the optical as part of the planning toward ELTs (e.g. Przybilla et al. 2009; Nieva et al. 2009), not to mention compilation of a high-resolution spectral library in the near-IR (Lebzelter et al. 2010; Ramsay et al. 2011).

A more detailed example of exploring alternative diagnostics is the recent study by Davies, Kudritzki & Figer (2010) in which they employ low-resolution ( $R \sim 2\text{-}3000$ )  $J$ -band spectroscopy to determine metallic abundances for red supergiants – this is a relatively unexplored wavelength domain, first considered for this type of abundance work by Origilia et al. (2004). From comparisons with contemporary model atmospheres, the method provides good estimates of stellar metallicities (with a dispersion of  $\pm 0.14$  dex) for library spectra in the Solar neighbourhood; example fits are shown in Fig. 5. We are now exploring the potential of this method for metal-poor templates in simulated ELT observations, using the tools mentioned earlier that were developed for EAGLE. By their nature, red supergiants are cool (i.e. significant  $J$ -band flux in their spectral energy distributions) and



very luminous - when combined with the AO capabilities of the ELTs, this method could provide a probe of stellar abundances out to distances of tens of Mpc.

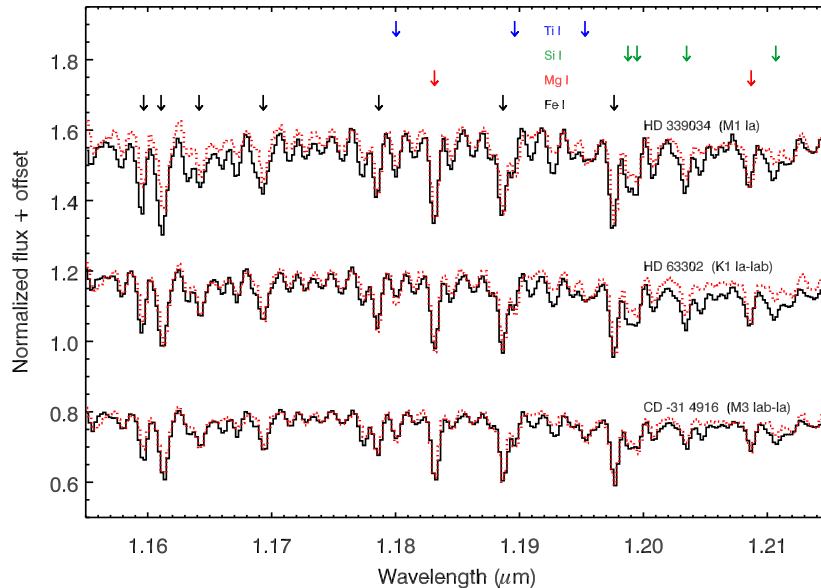


Figure 5: Model atmosphere fits (red lines) to provide metallicities/stellar abundances from *J*-band spectra of Galactic red supergiants (Davies, Kudritzki & Figer, 2010).

## 4 MAD: An AO pathfinder for ELTs

Correction for the effects of atmospheric turbulence with AO is a critical ingredient of the plans for ELTs and their instruments. In particular, there is a strong desire for good and *uniform* correction over larger fields-of-view than delivered by, e.g., VLT-NACO (Rousset et al. 2003). A key technical component within ESO's plan toward the E-ELT was an on-sky demonstration of multi-conjugate adaptive optics (MCAO). To this end, the Multi-conjugate Adaptive optics Demonstrator (MAD) was developed (Marchetti et al. 2007) with commissioning at the VLT in early 2007.

MAD employs three wavefront sensors to observe three natural guide stars across a  $2'$  circular field, thereby allowing tomography of the atmospheric turbulence. The turbulence is then corrected using two deformable mirrors, one conjugated to the ground-layer (i.e. 0 km), the second conjugated to 8.5 km above the telescope. The MAD near-IR camera critically samples the diffraction-limited PSF at  $2.2\mu\text{m}$ , giving a pixel scale of  $0''.028/\text{pixel}$ . With a  $2\text{k}\times 2\text{k}$  Hawaii-2 array, this gives a total field-of-view of  $57''\times 57''$ .

The commissioning performances were sufficiently compelling that ESO issued a call for Science Demonstration (SD) observations, to which the community responded enthusiastically. As an illustration of the SD programmes I refer to *H*- and *K<sub>s</sub>*-band MAD observations of R136 (Fig. 6; Campbell et al. 2010), the dense cluster at the core of 30 Doradus in the Large Magellanic Cloud. Also of direct relevance to the topic of this meeting are the MAD observations of Trumpler 14 (Sana et al. 2010).

The AO correction is such that the mean full-width half-maximum of the PSFs is  $\sim 0''.10$  in two of the three MAD pointings (the best placed with respect to the guide stars). This provides near-comparable angular resolution to optical imaging with the *HST* (e.g., Hunter et al. 1995). Due to the size of the primaries, the angular resolution from MAD is finer than that from the *HST* at the same wavelength, although the *HST* has a large advantage in terms of sensitivity due to the reduced

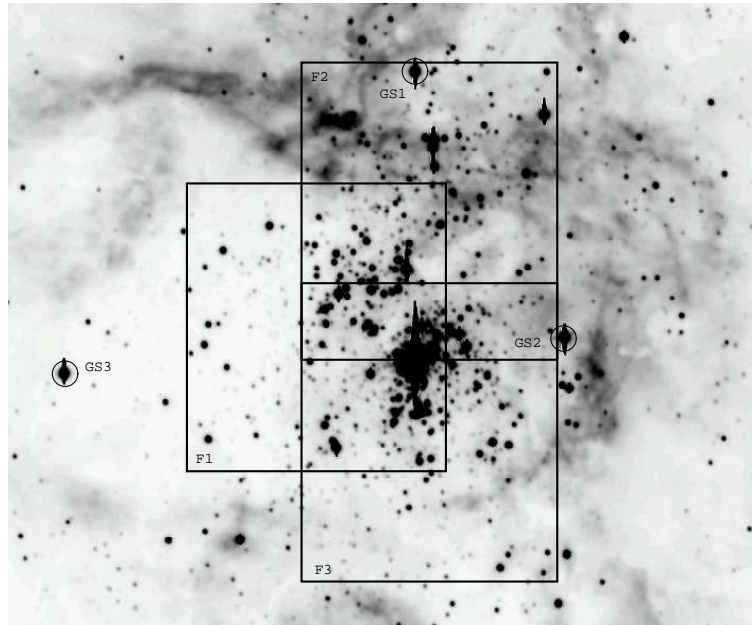


Figure 6: The three MAD pointings overlaid on a *V*-band image of the central part of 30 Dor. North is at the top, east toward the left. The three reference stars used for the AO correction are shown ('GS#').

sky background (cf. the results of Andersen et al. 2009). Further details regarding calibration and performance are given by Campbell et al. (2010); a combined image of the central region is shown in Fig. 7.

A nice test of the ground-based methods with MAD, compared to the *HST* results from Andersen et al., is provided by the agreement in the derived slopes of power-law fits to the luminosity profile of R136. The MAD data also have the advantage of going out to larger cluster radii than those from Andersen et al., allowing re-investigation of a 'bump' seen in the luminosity profile of R136 from optical *HST* observations (Mackey & Gilmore, 2003). This 'excess light' at large radii has been suggested in the past as perhaps related to the signatures of rapid gas expulsion from young clusters (e.g. Goodwin & Bastian, 2006). In contrast, the MAD data do not reveal an obvious break in the luminosity profile, with Campbell et al. (2010) suggesting that cluster asymmetries are the dominant source. In combination with AO-corrected IFU spectroscopy (Schnurr et al. 2009), the MAD data have since been used to argue that the central stars of R136 have initial masses in excess of  $150 M_{\odot}$  (Crowther et al. 2010).

The instrumental and scientific experiences of MAD augur well for the AO plans for ELTs. Pathfinders for other AO modes such as Multi-Object Adaptive Optics are underway, for example the CANARY project (Myers et al. 2008; Morris et al. 2010) and plans for RAVEN (Conan et al. 2010). In the shorter term, the Gemini MCAO System (GeMS) is now undergoing its final tests and integration (Neichel et al. 2010), and will offer a unique capability of MCAO with laser guide stars (removing some of the constraints on natural guide stars), for near-IR imaging and multi-object spectroscopy.

## 5 Summary

The ELTs offer huge potential for studies of massive stars – we will be able to address fundamental questions regarding their formation and evolution (with a particular focus on environmental effects), while also using individual stars as tracers of the stellar populations in galaxies well beyond the Local



Figure 7: Combined mosaic of the central  $40'' \times 40''$  MAD images (blue:  $H$ ; red:  $K_s$ ; green: interpolated).

Group.

By way of further motivation, consider the ground-breaking study by Swinbank et al. (2010) in which they have used multi-wavelength observations to study a gravitationally-lensed galaxy at a redshift of  $z = 2.3$ . By virtue of the lens, individual star-forming regions are resolved in sub-millimetre imaging, each  $\sim 100$  pc in scale – i.e. direct observation of intense regions of star formation with spatial extents comparable to that of 30 Doradus, at a time when the universe was significantly younger. Such an observation is only possible at present due to the magnification of the lens but, with the combined power of ALMA and the ELTs in the future, we can expect comparable observations in unlensed systems. One of the challenges ahead is to improve our models of stellar evolution to the point at which we are confident that we can interpret integrated-light spectroscopy of such distant systems accurately, thereby exploiting our understanding of massive stars to obtain new insights into the processes at work during the critical epoch of galaxy evolution.

## Acknowledgements

Thanks to Michael Campbell for his MAD mosaic and to Ben Davies for copies of his figures.

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## Discussion

**R. Chini:** What will be the contribution of this new generation of ELTs instruments to the investigation of Galactic high-mass (say e.g.  $V < 10$  mag) stars? Are there currently any estimates about the brightest stars that can be (are allowed to be) observed, say with the ELT?

**C. Evans:** You could imagine using a high-spectral resolution instrument to do time resolved studies, but you would have to consider if it's the most efficient telescope if, say, an 8-m class would do. In terms of brightness limits, there are no constraints I know of. Persistence in IR detectors is less of a problem than it used to be but you might have to worry about scattered light issues, for example.

**H. Zinnecker:** You kindly mentioned ELTs power to penetrate large amounts of extinction ( $A_V = 100 - 200$ ). Indeed, simulations carried out at ESO show that the E-ELT can be used to study the stellar content of very heavily obscured, young protoclusters, in particular the central stellar density of massive young stellar objects. This will be important new information, in order to judge if stellar collisions or interactions are likely to occur in the earliest stages of high-mass star formation found in Galactic Infrared Dark Clouds (IRDCS). Exciting times ahead !

**C. Evans:** Thanks. I was hoping you would pick-up on this point !