EAGLE: An Adaptive Optics Fed, Multiple Integral Field Unit, Near-infrared Spectrograph

Simon Morris[1]
Jean-Gabriel Cuby[2]

[1] Department of Physics, University of Durham, United Kingdom
[2] Laboratoire d'Astrophysique de Marseille, France

Team members:
Steven Beard[1], Saskia Brierley[1], Mathieu Cohen[2], Jean-Gabriel Cuby[3], Nigel Dipper[4], Chris Evans[1], Thierry Fusco[5], Eric Gendron[6], Peter Hastings[1], Pascal Jagourel[2], Philippe Laporte[2], David Lee[1], David Le Mignant[3], Matt Lehnert[2], Fabrice Madec[3], Helen McGregor[1], Tim Morris[4], Richard Myers[4], Phil Parr-Burman[1], Mathieu Puech[2], Gerard Rousset[6], Hermine Schnetler[1], Brian Stobie[1], Mark Swinbank[4], Gordon Talbot[4], Sebastien Vives[3], Pascal Vola[3], Martyn Wells[1]

[1] UK ATC, [2] GEPI, Obs. de Paris, [3] LAM, [4] Durham Univ., [5] ONERA, [6] LESIA, Obs. de Paris

EAGLE will provide spatially-resolved (3D) spectroscopy in the near-infrared of ≥ 20 science targets (e.g., faint galaxies) simultaneously. It will sense and correct distortions from the atmosphere using multi-object adaptive optics, giving it an unrivalled survey efficiency even in the JWST era.

Science drivers

A multi-Integral Field Unit (IFU) spectroscopic capability accessing a wide field, fed by high-order adaptive optics, and operating at near-infrared (NIR) wavelengths, has been a common aspiration of all ELT projects from the outset. Such an instrument is required to answer many of the most exciting and vexing questions in contemporary astrophysics. EAGLE is a general facility instrument that will serve a broad community of users. It uses the E-ELT at its best, over a wide field of view and with AO-corrected images.

One of the dominant scientific motivations for the E-ELT is the study of galaxy evolution. This encompasses a huge range of phenomena and scales — from studies of resolved stars in nearby galaxies, right out to our attempts to understand the properties of the most distant galaxies near the dawn of time. From consideration of these cases, and the broader astrophysical landscape, a set of science requirements were compiled for a NIR spectrograph with multiple, deployable IFUs. The three principal science cases used to optimise the EAGLE design were (in decreasing redshift order):

– First light: galaxies at the highest redshifts. Current estimates of surface densities at $z > 7$ are well-matched to the EAGLE-designed surface densities, even after correction for the fraction that will not be suitable as they have features at wavelengths blocked by sky emission. By combining JWST imaging and low dispersion slit spectroscopy with EAGLE's ability to deliver spatially resolved $R = 4000$ spectroscopy, even for objects of the sizes predicted at $z > 7$, the physics of the first light objects will be determined.
– The physics of high-redshift galaxies. See Figure 1 and Puech et al. (2010) for detailed modelling and discussion of this science case.
– Resolved stellar populations in the local volume. See Evans et al. (2010a) for an extended discussion of this science case. The EAGLE multiplex, combined with the ability to obtain spectra from multiple stars with each IFU field, and its wavelength coverage below the Ca triplet in the rest frame, make it ideal for this stellar archaeology case.

Detailed science simulations were undertaken to quantify the requirements, employing the tools developed by Puech et al. (2010) to generate simulated IFU datacubes for each of the principal cases (see Figure 1 for an example drawn from the Design Reference Mission galaxy formation science case).

The resulting instrument requirements (Table 1) have been used to develop the EAGLE concept, which combines superb image quality (via AO correction) with a wide field of view.

Instrument design concept

EAGLE is located at the Gravity Invariant Focal Station (GIFS) of the E-ELT (see Cuby et al., 2009 and Figure 2). It consists of 20 IFU

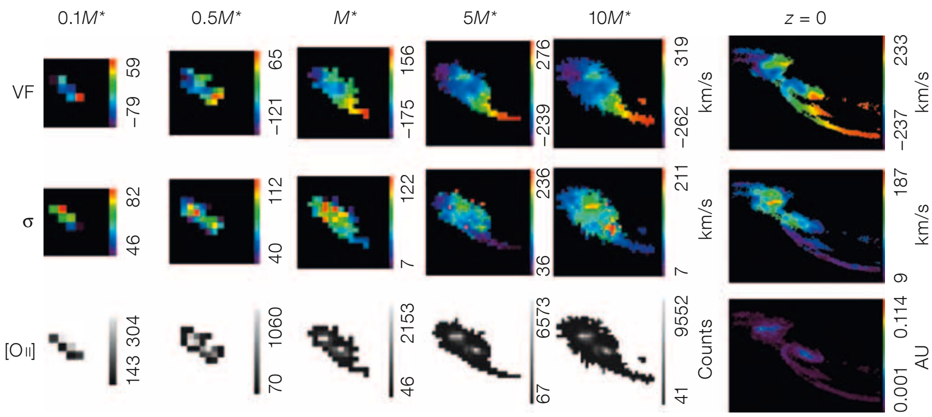

Figure 1. Simulated EAGLE observations of a major merger at $z = 4$ (Puech et al., 2010), with the input template ($z = 0$) shown on the right-hand side. The simulations are shown as a function of the characteristic galaxy mass (M^*); upper panels: recovered velocity field; central panels: recovered velocity dispersion; lower panels: recovered emission-line map.

spectrographs deployable (via pick-off mirrors) over a patrol field of 38.5 arcminutes^2. Each IFU has an individual field of view of ~ 1.65 × 1.65 arcseconds. Pairs of IFUs are integrated into a single spectrograph and illuminate a 4k × 4k detector. Each IFU spectrograph is housed in a small cryostat (~ 1500 mm long and 600 mm diameter). One of the *IZ*-, *YJ*-, *H*- or *K*-bands can be observed at a time resulting in a spectral resolution of ~ 4000. A high resolution mode of 10 000–13 000 is offered for stellar work. Each channel is equipped with its own deformable mirror (DM) for AO correction. There are wavefront sensors for six laser guide stars and five natural guide stars. There is a high level of duplication and redundancy in the instrument, providing robustness against single-point failures and easing maintenance. EAGLE is, in essence, a single-mode instrument.

EAGLE, in its default mode, uses Multi-Object Adaptive Optics (MOAO, see Figure 3 and Rousset et al., 2010). MOAO is just one more flavour of wide-field AO, as are LTAO, GLAO or MCAO. It is conceptually simple: once the atmospheric turbulent volume above the telescope is measured with tomographic techniques, the correction needed at a given position in the field of view is derived by a simple projection and is performed by a local DM. MOAO has now been demonstrated in the laboratory and there are several programmes underway to further characterise it on sky, in Europe as part of the EAGLE technology development plan (CANARY at the WHT) and in the US and Canada. EAGLE provides an

Table 1. Instrument requirements for EAGLE.

Patrol field	≥ 5 arcminute diameter
Science (IFU) field	≥ 1.5 × 1.5 arcseconds
Multiplex (no. science fields)	≥ 20
Spatial pixel scale	37.5 milliarcseconds
Spatial resolution	Encircled energy ≥ 30 % into 2 × 2 spatial pixels
Spectral resolving power	4000 and ≥ 10 000
Wavelength coverage	*IZ*-, *YJ*-, *H*-, *K*-bands (0.8–2.45 μm)
Clustering/tiling	Distributed and clustered targets + ability to map contiguous regions

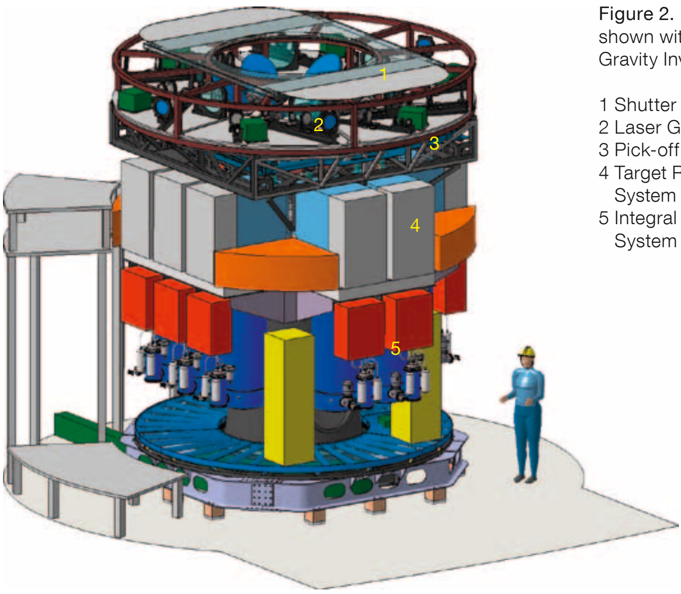

Figure 2. EAGLE mechanical design, shown within the footprint of the E-ELT Gravity Invariant Focal Station.

1 Shutter
2 Laser Guide Star Sensing System
3 Pick-off System (Focal Plane)
4 Target Reimaging and Magnification System (including Deformable Mirror)
5 Integral Field Unit and Spectrograph System

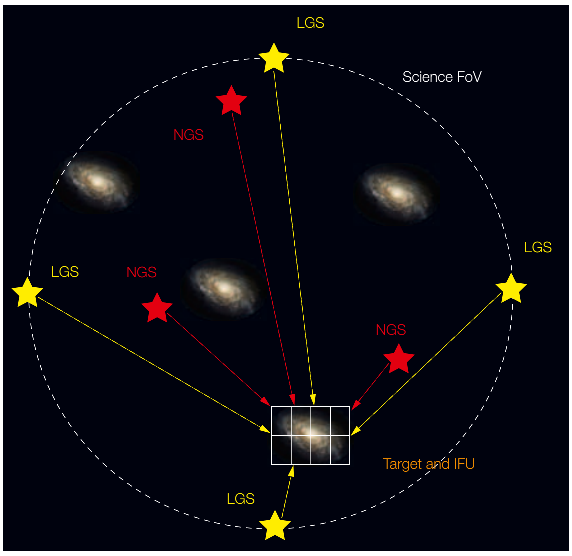

Figure 3. EAGLE will use a wide-field, multi-object adaptive optics system to correct the wavefront errors for each integral field unit (only one shown), using a combination of laser and natural guide stars to map the atmospheric turbulence.

image sampling of the order of 50–100 milliarcseconds, which is a robust trade-off between AO performance, sensitivity, scientific requirement and cost.

By construction (with DMs flat), EAGLE can also operate in GLAO or LTAO modes as the telescope AO is gradually deployed. EAGLE will reproduce several telescope wavefront sensing functions (laser and natural guide stars) at the GIFS in a manner that will be transparent to the rest of the E-ELT systems. Because of this flexibility EAGLE could be used soon after first light for the E-ELT. To support this possibility, EAGLE has been designed using a coordinated systems engineering approach, with a carefully thought-out development plan. We have already had a number of interactions with possible industrial partners, and have an assembly, integration and test plan that includes pre-production of a single channel, to ensure that costs and risks for the whole instrument are minimised.

Performance

Performance estimates of EAGLE suggest that it will achieve a signal to noise ratio (SNR) of ~ 5 per spectral resolution element in 30 hours on a point-like (or slightly resolved object) of AB magnitude 27 in the *J*- or *H*-bands. This is ~ 2 magnitudes fainter than that which JWST will achieve. For detailed spectroscopic investigations of the most distant galaxies discovered by JWST and for robust 3D studies of high-redshift galaxies, no other facility will be able to compete efficiently with EAGLE on the E-ELT which, in combination with ALMA, will provide us with unprecedented insight into the physical processes that drive galaxy formation and evolution. EAGLE will capitalise on the expertise in highly parallel 3D spectroscopic instruments developed by the MUSE and KMOS projects (which are often presented as E-ELT instrument precursors). Roughly speaking, EAGLE is the E-ELT counterpart of KMOS, with the added AO functionality and with an immensely superior scientific capability. When used in synergy with ALMA and JWST, the E-ELT, if equipped with EAGLE, will allow us to see the first objects to collapse to form stars in the Universe and understand how the majority of galaxies on the Universe are assembled, tracing their evolution from redshifts of more than eight to the present day.

A more extended and less technical description of the EAGLE science case and technical properties is given in Evans et al. (2010b).

References

Cuby, J.-G. et al. 2009, SPIE, 7439, 13
Evans, C. et al. 2010a, Proc. 1st AO4ELT conference, eds. Y. Clénet et al., EDP Sciences
Evans, C. et al. 2010b, Astronomy and Geophysics, 51, 2.17
Puech, M. et al. 2010, MNRAS, 402, 903
Rousset, G. et al. 2010, Proc. 1st AO4ELT conference, eds. Y. Clénet et al., EDP Sciences