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L. Cambrésy, F. Martins, E. Nuss and A. Palacios (eds)

MOSAIC AT E-ELT: A MOS FOR ASTROPHYSICS, IGM AND COSMOLOGY

F. Hammer[1] and (on behalf) the MOSAIC team

Abstract. The Universe includes hundreds of billions of galaxies, each of them being populated by hundreds of billions of stars. Astrophysics aims to understand the complexity of an almost incommensurable number of stars, stellar clusters and galaxies, including their spatial distribution, their formation and their current interactions with the interstellar and intergalactic media. A considerable fraction of discoveries in astrophysics require statistics, which can only be addressed by a MOS. A visible/near-IR MOS with capacities adapted from stellar physics to cosmology is technically feasible as recent studies have demonstrated that key issues like sky background subtraction and multi-object AO can be solved.

The E-ELT, which will be the world's largest optical/IR telescope in the 2020s, has to be equipped as soon as possible with a MOS that allows the largest discovery space. The MOS at the E-ELT will be unique to probe the sources of reionisation, to investigate their physics, to study the galaxy mass-assembly history including high-z dwarves, to describe the distribution of the IGM, as well as probing resolved stars at unprecedented distances, from the outskirts of the Local Group for main sequence stars, to a significant volume including nearby galaxy clusters for luminous red supergiants.

Keywords: instrumentation, astrophysics, galaxies, stars

1 Introduction

During the 1990s, the first multiple object spectrographs implemented at the Anglo-Australian and Canada-France-Hawaii Telescopes have produced major breakthroughs simply by multiplying by huge factors the size of the observed Universe. For example, the Canada France Redshift Survey (Hammer et al. 1995; Le Fevre et al. 1995; Lilly et al. 1995) was the first to gather a complete sample at z$\sim$ 1 corresponding to a volume of 150 Gpc^3, instead of 1 Gpc^3 at z$\sim$ 0.15 previously investigated. All the 8 meter-class telescopes are currently equipped with multiple object spectrographs, which gather most of the observing time, and lead to a considerable fraction of the discoveries. LRIS has given to the Keck the glory to be the first in identifying the population of Lyman break galaxies at z$\sim$ 3 (Steidel et al. 1996). At VLT, FORS has revealed the pre-existence of early type galaxies at z >1, and FLAMES has provided the first metal abundances in the dwarf spheroids in the vicinity of the Milky Way by measuring numerous stars at once. There is also a massive investment at VLT with a large community support for wide field, MOS instruments (e.g., KMOS and MUSE).

The crucial need for a MOS, obvious for 4 and 8 meter-class telescopes, still stands for $\geq$ 30 meter-class telescopes. The advent of the ELTs will allow the detection of primordial sources in the Universe as well as to providing detailed diagnostics of sources that are merely detected by present-day telescopes (e.g., galaxy population up to the re-ionization epoch, low-mass & dwarf galaxies at all epochs, individual stars and stellar clusters in galaxies well outside the Local Group etc). The best solution for a MOS is to sample the largest discovery space in terms of wavelength range, spectral and spatial resolutions, and multiplex. Modern astrophysics also requires multiple integral field units (IFUs) at ELTs. Only such devices can measure the kinematics of the gas in very distant galaxies, and are superior to any other system in removing the sky signal, as it can be estimated from pixels surrounding the source of interest.

The MOSAIC white paper (see Evans et al. 2013) highlights six key science cases, from resolving individual stars outside the Local Group to cosmology. We must add, however, that we have been very impressed by the far

[1] GEPI, Observatoire de Paris, UMR 8111, CNRS

larger number of science cases that have been presented during the ELT-MOS meeting in Amsterdam (October 2012) and several national ELT-MOS meetings in different European countries and in Brazil. To account for most of them, we have defined two preferential modes, one with high multiplex (HMM, multiplex=100 to 250, GLAO or seeing resolution), and one with high spatial definition (HDM, MOAO IFUs, multiplex=10 to 20, pixel size from 40 to 80 max). During the writing of the white paper, we have realized that almost all sciences cases will highly benefit from the combination of these two modes, leading to an up-date of the document before 2014.

2 MOSAIC is unique for understanding physics of galaxy & star formation

The scientific objectives of MOSAIC essentially gather those of EAGLE (Cuby et al. 2010) and of OPTIMOS-EVE (Hammer et al. 2010). Combination of high multiplex with different spectral resolutions (R=3000-5000 and R=20000) allows to study individual stars in various environments as well as to study abundances and star formation histories of dwarf galaxies up to z=4. The high multiplex mode with fibers could be slightly less efficient than slits in recovering spectra of ultra-faint objects, though current efforts in optimizing sky-subtraction are very encouraging for reaching accuracy down to 0.4-0.6% of the sky continuum (Yang et al. 2013). Nevertheless, multi-slit spectroscopy is mostly adapted to low resolution spectroscopy that is focused to redshift survey and gross estimates of few quantities. Spectral resolutions from 3000 to 10000 are mandatory for resolving even the smallest galaxies seen in the early epoch of the Universe, in order to properly measure extinctions, star formation rates (see, e.g., Liang et al. 2004), O/H abundances, and especially, kinematics. Such resolutions are generic for fiber spectrographs, and are also mandatory for a proper removal of sky emission lines above 0.72μm.

MOSAIC is potentially the instrument at an ELT that will provide the deepest and most complete insights into the physics of the first galaxies (see contribution by J. G. Cuby, same volume). In fact armed with multiple IFUs, MOSAIC would be able to identify the main physical processes of galaxy formation, since the earliest light in the Universe. The potential of MOSAIC combined with deep imagery at exquisite spatial resolution such as that provided by JWST and E-ELT-CAM, will be without any competitors within the next decades.

To illustrate this, let us compare what has been learnt about galaxy formation from the combination of the VLT and of the HST. With this combination, the deepest and most complete observations of intermediate distant galaxies (z$<$ 1) are rather comparable to what can be done in the nearby Universe, allowing to study the ancestors of present-day galaxies, 6 to 8 billion years ago. Observations included spatially-resolved kinematics from VLT, detailed morphologies from HST and photometry from UV to mid-IR (Spitzer). Six billions years ago, half of the present-day spirals were starbursts experiencing major mergers, evidence for this is provided by their anomalous kinematics and morphologies (Yang et al. 2008; Neichel et al. 2008; Delgado-Serrano et al. 2010). They have been consequently modeled using hydrodynamics models of mergers (Hammer et al. 2009) and it perfectly matches with merger rate predictions by state-of-the-art-ΛCDM semi-empirical models (Hopkins et al. 2010; Puech et al. 2012). Furthermore imprints in the halo of local galaxies such as NGC5907 are likely caused by major merger relics (Wang et al. 2012). This suggests that the hierarchical scenario has played a major role in shaping the massive galaxies of the Hubble sequence (Hammer et al. 2005, 2009). Nowadays, most cosmological simulations (see e.g., Aumer et al. 2013 and references therein) -if not all- are predicting the rebuilding of spiral disks after major mergers, which orbital imprints have settled the disk angular momentum.

A similar, complete investigation of the physical properties of z$>>$ 1 galaxies is presently out of reach, mostly because of their faintness (up to 26-27 AB magnitudes) and compactness (stellar half light radius down to 0.1-0.2 arc sec). Thanks to their considerably large diameters and to the development of adaptive optics, including multiple object adaptive optics (see, e.g., Assemat et al. 2007), E-ELT/MOSAIC and JWST together could be the successful combination to investigate the physics of the first instants of galaxy formation, near or at the time the Universe was still not re-ionized. Such a combination will not be challenged at other 30m-class telescopes, because those will not be equipped with multi-IFUs but with multi-slit spectrographs. In a similar way, MOSAIC will estimate abundances of individual stars in galaxies far outside the Local Group, including Red Supergiants up to 35 Mpc, i.e., in any kind of galactic type or of environment. Here again, MOSAIC will be without competitors because of its relatively large multiplex mode at R= 5000 to 20000 (Davies et al. 2010; Evans et al. 2010).

3 Present status of MOSAIC

The MOSAIC team is led by a France-UK-Netherlands-Brazil consortium, with a strong support from other ESO members, such as Austria, Germany, Italy & Sweden. The core-team includes scientists and engineers who were leading or taking important responsabilities into the realization of FLAMES/GIRAFFE, X-SHOOTER, ISAAC, NACO and KMOS at VLT.

The first activity has been to re-evaluate scientific objectives of both EAGLE and EVE, in the context for which the two first-light instruments have been decided by ESO. This work has been and is currently done by the Science Team that includes 66 scientists from the overall Europe and Brazil, and most of the key Science Cases have been tested using an end-to-end, open-access simulator, realized and maintained at the Paris Observatory (Puech et al. 2010). High level science requirements are now at a stage for which a compromise should be done between, e.g., the HDM pixel size, the possible extent to the K-band, and the HMM multiplex value. Adaptive optics of MOSAIC is also under study, for optimizing the correction, while keeping the complexity/cost reasonable. Other important requirements are also under study requiring simulations of characteristic science cases, such as the wavelength range accessible in one exposure or the aperture size of the HMM fibers. Operating modes and the possible advantage of combining them during the same exposure is also under study. The team is pursuing its effort on improving the best method to subtract the sky with fibers and IFUs. The latter activity has been also useful for MOONS, which is a near-IR fiber fed spectrograph recently selected as a third generation instrument for the VLT, and which is also led by a part of the MOSAIC team.

The technical team has now defined two possible, generic solutions for MOSAIC. The first one allows the two modes (HMM and HDM) to share the same plateau, the second one is envisioning one plateau per mode ("a la FLAMES"), implying that visible and NIR spectrographs are linked to the focal plates by fibers. Both solutions have their advantages and disadvantages, and a final trade-off is expected, probably next year, at the time ESO is expected to launch a Call for an ELT-MOS. As described above, the overall goal of the MOSAIC team is to prepare a relatively versatile instrument for the E-ELT, which has also to be simple and operable enough. Though such a goal could appear unrealistic for the considerable versatility of MOSAIC, we have learned from FLAMES that fibers are quite powerful to limit the complexity and operability risks for multi-mode instruments.

4 Conclusions

A significant part of the European and Brazilian scientific community is supporting the rapid implementation of a MOS at the E-ELT. The combination of ELT-MOSAIC with JWST and other imagers such as ELT-CAM, will be without competitors to investigate physical properties of galaxies since the earliest time of their formation. Their morphologies will be compared to their internal motions from spatially resolved spectroscopy, and together with important physical quantities (masses, SFR, O/H), one will resolve the way galaxies are forming from the primitive gas-rich Universe. Similarly, a relatively large multiplex at R= 5000 to 20000 would make MOSAIC unique for investigating individual stars in a large volume, up to 35 Mpc, allowing to investigate them in every kind of galactic type and of environment.

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