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FORMATION AND EVOLUTION OF GALAXIES WITH THE ELT AND MOSAIC

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Abstract. We present in this contribution the status of the MOSAIC project after Phase A (conceptual design). One of the main scientific driver for MOSAIC will be the formation and evolution of galaxies for which a multi-IFU MOAO-assisted mode was designed ('High Definition Mode'). Two of the four proposed MOSAIC highlight surveys are related to this science case with (1) the assembly and evolution of dwarf galaxies and (2) the inventory of (dark) matter in distant galaxies. Finally, we review the instrument trade-offs related to the dimensioning of the HDM IFUs and the resulting high level specifications for the MOAO system. As designed, the multi-IFU HDM mode of MOSAIC will be highly complementary observations to the single, larger FoV IFU offered by HARMONI on the ELT.

Keywords: Spectroscopy, ELT, galaxies, formation, evolution, kinematics

1 Introduction: summary of project status after Phase A

The 39m Extremely Large Telescope (ELT) will be the largest optical-near infrared telescope in the coming decades. It will be equipped with a suite of instruments which span the parameter space required to address a large collection of science cases that were developed over the past 15 years*. The first-light instrument suite (i.e., MICADO† and HARMONI‡) will largely exploit the exquisite spatial resolution (and depth) provided by the ELT, as well as the mid-infrared window (METIS§). The two other first generation instruments will provide access to high resolution spectroscopy (HIRES¶) and multi-object spectroscopy (MOSAIC‖).

The detailed science case for a multi-object spectrograph (MOS) on the ELT was initially developed in the context of the ESO Design Reference Mission (e.g., Puech et al. 2008, 2010) and during Phase A studies of the EAGLE (e.g., Evans et al. 2010) and OPTIMOS (Navarro et al. 2010; Le Fèvre et al. 2010) concepts. More recently, the case for an ELT-MOS was assembled from consultation with the European user community (and beyond), as presented in the ELT-MOS White Paper (Evans et al. 2015). The White Paper formed the initial core of the MOSAIC science case, and was used to inform the top-level requirements (TLRs) for the conceptual Phase A study, undertaken between March 2016 and March 2018. Detailed scientific simulations with the WEBSIM-COMPASS software (Puech et al. 2016) were used to assist with science trade-offs in the study, while several new science cases were also identified and added to the initial list. The Science Team prioritized four highlight cases for future MOSAIC observations, and defined potential surveys that were simulated and dimensioned using the MOSAIC conceptual design, which was finalized in parallel by the technical team (Jagourel et al. 2018). The status of the MOSAIC Science Case at the end of Phase A and a description of the potential surveys are described in Puech et al. (2018) (hereafter: P18).

Here we focus on the science cases related to galaxy formation and evolution, and in particular to those related to galaxy spatially-resolved kinematics, which is the most demanding in terms of signal-to-noise (S/N). To address these science cases, the MOSAIC conceptual design incorporates a dedicated observational mode

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*`https://www.eso.org/sci/facilities/eelt/science/doc/eelt_sciencecase.pdf`

†`http://www.mpe.mpg.de/ir/micado`

‡`http://www-astro.physics.ox.ac.uk/instr/HARMONI/`

§`http://metis.strw.leidenuniv.nl/`

¶`http://www.hires-eelt.org/`

‖`http://www.mosaic-elt.eu/`

(amongst the 4 observational modes proposed, see Jagourel et al. 2018). In this High-Definition Mode (HDM), it will be possible to conduct simultaneous observations of 8 IFUs (goal: 10 IFUs) deployed within a ∼40 arcmin^2 patrol field and each with enhanced image quality from multi-object adaptive optics (MOAO, see Morris et al. 2018b). Each IFU will cover a 1.9" hexagon with 80mas spaxels, with the spectrographs delivering R∼5000 over 0.8-1.8μm (between 250 and 430nm in one observation). A high spectral-resolution set-up will provide R∼20 000 over a passband ∼100nm at 1.6μm. A complete technical and project overview can be found in Jagourel et al. (2018) and Morris et al. (2018a), respectively.

2 Understanding the formation and evolution of galaxies through cosmic times with MOSAIC

Advancing the field of galaxy formation requires a comprehensive census of the mass assembly, star-formation histories, and stellar populations in galaxies. MOSAIC will deliver several advances in the field by measuring the stellar kinematics in z∼1 galaxies or in sub-structures of local systems. In particular, measuring the stellar kinematics of the tidal debris expected to lie in the outskirts of most Milky Way-like systems will allow us to test theoretical predictions and learn about the processes by which these galaxies formed (Toloba et al. 2016), and provide unique views on their dark matter halos (Errani et al. 2015). At earlier epochs (2<z<4), it will be important to measure spatially-resolved chemo-dynamical information in galaxies across a wide range of stellar masses (dwarfs to giants) and environments (field to clusters). Such observations will allow us to measure accurately the evolution of the fraction of rotationally-supported galaxies vs. mergers out to z∼4, to study the evolution of important scaling relations and quantities such as the Tully-Fisher relationship, evolution of the velocity dispersion and specific angular momentum, and to derive the internal distribution of metals. Within this context, the HDM mode of MOSAIC will be particularly well-suited to explore two new territories: (1) the mass assembly and evolution of dwarf galaxies and (2) the inventory of dark matter in the distant Universe. These two cases are the core of two of the four highlight surveys that were proposed for MOSAIC (P18).

2.1 Mass assembly and evolution of dwarf galaxies

Dwarf galaxies are expected to play a key role in galaxy formation and evolution. In hierarchical models they are thought to be the first structures to form in the Universe and are believed to have an important contribution to the reionisation process. Investigating the detailed properties of dwarf galaxies and their relation to the more massive population at z>2 is therefore an important test of structure formation in ΛCDM. Observations are currently limited by their faint apparent magnitudes and we have limited knowledge of their spatially-resolved properties (Contini et al. 2016). This domain will probably remain only partially explored until the next generation of integral-field spectrographs on the ELTs (and JWST).

The first objective of this survey will be to measure the spatially-resolved kinematics of z=2-4 galaxies using the HDM IFUs. When combined with deep imaging (rest-frame near-IR) which traces galaxy morphology, we will infer the dynamical state of distant galaxies and investigate the evolution of the fraction of virialised rotating disks vs. unvirialised systems such as mergers (see, e.g., Rodrigues et al. 2017). Connecting the distant dwarf population to the more massive galaxies will require mass-representative observational samples covering a large range in mass. A specific survey was designed and simulated, with two redshift ($z = 2$ and $z = 4$) and three mass bins (sampling sub-M*, M*, and super-M* galaxies at both redshifts, see Puech et al. 2010). This spatially-resolved kinematic survey will require pre-existing deep imaging down to $H_{AB} \sim 25$ with good spectroscopic completeness, within reach of facilities such as JWST-NIRCam or Euclid (imaging) and VLT-MOONS or JWST-NIRSpec (spectroscopic redshifts). To have the internal statistics of each bin limited only by Poisson fluctuations, we need at least 50 galaxies per bin and explore 3 independent fields (to control cosmic variance effects), which leads to a total survey of ∼1 000 galaxies (P18).

The spatially-resolved spectroscopy of sub-M* galaxies at z=4 at sufficient R to resolve their internal motions will be a unique case for MOSAIC cf. JWST-NIRSpec. The latter will provide measurements at similar spatial scales (∼100 mas) but will be limited to R=2700. The HR spectral set-up (R=20,000) will allow us to resolve emission lines down to 15km/s in specific redshift windows, enabling motions to be resolved in distant LMC-like dwarfs at z∼1.3-1.5 and z∼3.1-3.4 using Hα or [OII], respectively. Such observations will provide important constraints on the star-formation history (e.g., Pacifici et al. 2012) of this population, as well as estimates of star-formation rates and metallicities from their emission lines. This case also provides strong synergies with HARMONI as several sub-samples drawn from the MOSAIC parent survey could be followed-up at higher spatial resolution to study, e.g., the non-circular motions occurring at smaller spatial scales (e.g., bars, warps) or instabilities such as clumps, which might play an important role in galaxy evolution and formation. For instance, simulations by Zieleniewski et al. (2015) have shown that such irregularities within the optical radius of z∼2 galaxies can be recovered with HARMONI using 20mas spaxels and integration times of 10hr.

2.2 Inventory of dark matter

Dark matter profiles can be estimated from accurate measurements of rotation curves (RC) in disk galaxies. This requires sufficient spatial resolution to resolve the shape of the rotation curve (particularly the inner part) and to avoid strong biases due to beam-smearing effects, as well as sufficient S/N out to at least two optical radii so that the plateau of the RC can be measured accurately to within a few percent (Bosma 1978; Epinat et al. 2010). Rotation curves can be measured on individual disk galaxies but binning can be used to increase S/N and smooth out the small-scale fluctuations associated with non-circular motions that are unrelated to the underlying mass distribution (e.g., bars, warps, etc.). First attempts to measure rotation curves in distant galaxies using binning were just obtained in galaxies at z∼2 at the VLT (Genzel et al. 2017), although with limited spatial extension and spatial resolution. In the local Universe, binning has been used to sample the luminosity function over ∼7 magnitudes (Lapi et al. 2018). The goal of this MOSAIC survey is to obtain similar information in galaxies out to z=4, for the first study of the evolution of dark matter content as a function of mass and redshift. This will provide new and important tests of structure formation in the ΛCDM paradigm and in cosmological simulations, such as the evolution of the stellar vs. halo mass relationship, the evolution of the star-formation efficiency, and the evolution of disk and halo angular momentum and whether these are conserved during disk formation as predicted (see, e.g., Lapi et al. 2018).

A dedicated survey will require a representative parent sample of galaxies which sample the galaxy mass out to z=4. To be meaningful, the RC measurements and dark-matter profile analysis have to be conducted in the sub-sample of galaxies that are truly rotating so that the observed kinematics can be safely related to the underlying mass distribution (which is not necessarily the case in, e.g., on-going mergers). The mass-assembly survey (see above) will provide a natural parent sample for this programme, from which a representative sub-sample of secure distant disk galaxies analogs to local spirals can be extracted. This parent survey is expected to offer at least ∼250 targets over z=2 to 4 in which the decomposition of the RC into mass profiles could be conducted. This number will also guarantee that the precision/accuracy of the resulting average RC constructed in each bin (∼0.15 dex comparable to similar studies in the local Universe, Lapi et al. 2018) is limited only by Poisson-noise fluctuations due to the limited number of galaxies per bin (P18). These observations will also require good extended photometry (with JWST-NIRCam or ELT-MICADO) to measure the optical radii of distant galaxies with 10% accuracy and to identify those with morphological types later than Sb to minimize the impact of the bulge on the rotation curve decomposition into mass profiles.

The limited FoV of the individual HDM IFUs (1.9" accross) will limit the accuracy of these measurements at z=2, because this will not allow to sample the RC at large enough radii as required. In principle, mosaicing several HDM observations could overcome this issue; although at the risk of possible additional systematics. To this respect, HARMONI and MOSAIC will be highly complementary since the former will provide a large enough FoV, while also offering higher spatial resolution, although for a single IFU/object. It will be therefore possible to characterize these possible systematics using a limited sub-sample and then obtain the required statistics with MOSAIC once these will be understood and controlled. For this specific science case, MOSAIC will be indeed 25 to 50 time faster than HARMONI (depending on R) to assemble the required sample (P18).

3 Dimensioning the MOSAIC HDM IFUs: instrument trade-offs

3.1 Spaxel scale vs. spatial resolution vs. survey speed

The dynamical state of galaxies is mostly imprinted on large-scale motions and depends weakly on the small-scale irregularities that are due to non-circular motions such as bars or warps (Puech et al. 2008). While a smaller spatial resolution allows to study structures at smaller scales, hence enlarging the scientific capabilities of the instrument, it also costs in terms of S/N since the latter scales linearly with the IFU spaxel scale in a background-limited regime. We used simulated observations to determine the range of spaxel scale in which the dynamical state of z=4 galaxies could be determined, and found an upper limit ∼80mas (Puech et al. 2008). With such a spaxel scale, the MOSAIC/HDM IFUs will indeed provide at least two spaxels per half-light radius even in 0.5M* galaxies at z=4 (Puech et al. 2010).

The S/N required to obtained IFU observations of galaxies as a function of mass and redshift was studied in detail during the E-ELT DRM (Puech et al. 2010). Adapting those results to the above survey, one finds that MOSAIC will be able to conduct this survey in $\sim$125 nights (assuming 8hr of observations per night and accounting for 30% overheads). This scales linearly with multiplex so that, for instance, decreasing/increasing the multiplex in HDM down/up to 4/10 would require 250/100 nights. This suggests that at least 8 IFUs in HDM are required to remain effective, and that increasing the number of IFUs from 8 to 10 would be highly desirable as it provides a direct gain of 20% in survey speed[**].

3.2 MOAO: the required Ensquared Energy

The coupling between the MOAO and the spectrograph can be quantified using the Ensquared Energy (EE), i.e., the fraction of the PSF entering an element of spatial resolution. Conversely to other flavors of Adaptive Optics systems such as LTAO or MCAO, MOAO does not aim at providing high spatial resolution (hence high Strehl Ratios) but rather aims at providing moderate spatial resolution but in N>1 directions spread over a large FoV (e.g., Hammer et al. 2004). Simulations have shown that EE>25% within 160mas (in H band) is required to distinguish between a rotating disk and an on-going major merger at z=4 (Puech et al. 2008). This was used as a high-level requirement for designing the MOAO system (Morris et al. 2018b).

4 Conclusions

MOSAIC will be the only ELT instrument providing NIR multi-IFU observations in the 2020s-30s. Improving the HDM multiplex will be amongst the top priority goals in the next design phases.

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[**] Defined as the ratio between the instrument multiplex and the total required observing time, see P18.