European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME

PERIOD: **93A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title

Category: **A–5**

Star formation, metallicity and AGN content of satellite galaxies at $0.8 < z < 1$

2. Abstract / Total Time Requested

Total Amount of Time: 0 nights VM, 12.0 hours SM

We will use KMOS to unveil the imprint of environment on the star-forming population of five groups and clusters at $z \sim 0.85$. Our extensive optical spectroscopy has shown, indirectly, that most of these galaxies must be undergoing observable transformations. To determine the nature and cause of this transformation, we will obtain near infrared integral field spectroscopy of ~ 100 star-forming galaxies, selected from our unparallelled sample of spectroscopically confirmed satellites with $M > 10^{9.3} M_{\odot}$. These new data will allow us to make spatially resolved maps of several key emission lines (Hα, [NII], [OIII], [OI] and Hβ) from which we will measure precise, dust-corrected star formation rates; map the spatial distribution of line emission; identify AGN through line diagnostics; and measure galaxy metallicity and large scale kinematics. By targeting galaxies with optical spectroscopy we are able to bring the full power of KMOS to bear on this longstanding and important problem.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	93	KMOS	1.4h	any	n	0.8	CLR	s	
B	93	KMOS	1.6h	any	n	0.8	CLR	s	
C	93	KMOS	1.4h	any	n	0.8	CLR	s	
D	93	KMOS	1.6h	any	n	0.8	CLR	s	
E	93	KMOS	1.4h	any	n	0.8	CLR	s	
F	93	KMOS	1.6h	any	n	0.8	CLR	s	
G	93	KMOS	1.4h	any	n	0.8	CLR	s	
H	93	KMOS	1.6h	any	n	0.8	CLR	s	

4. Number of nights/hours

Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:		
b) still required to complete this project:		

5. Special remarks:

6. Principal Investigator:

Sean McGee, mcgee@strw.leidenuniv.nl, NL, Sterrewacht,University of Leiden

6a. Co-investigators:

A.	Muzzin	Sterrewacht,University of Leiden,NL
H.	Hoekstra	Sterrewacht,University of Leiden,NL
R.F.J.	van der Burg	Sterrewacht,University of Leiden,NL
M.L.	Balogh	University of Waterloo,Department of Physics and Astronomy,CA

Following CoIs moved to the end of the document ...

7. Description of the proposed programme

A – Scientific Rationale: More than 30 years ago, it was shown that dense environments in the local Universe are dominated by quiescent, spheroidal galaxies, in contrast to the star forming disks abundant in the field (Dressler 1980). Observations and modeling have since shown that this is a characteristc feature of satellite galaxies; the difference is due to a quenching of star formation, and change in morphology, that is distinct from processes affecting normal, "central" galaxy evolution (e.g. Weinmann et al. 2006; Baldry et al. 2006; Peng et al. 2010). Despite advances in our ability to reconstruct the mass assembly and star formation histories of central galaxies (e.g. Behroozi et al. 2013, Patel et al. 2013), we still do not even have a good empirical picture of *how* the evolution of satellite galaxies differs, much less an explanation for why this should be so.
There are several physical mechanisms that could plausibly influence the evolution of satellite galaxies, and each has distinct observational consequences. Ram pressure stripping of the cold gas in a galaxy will create an elongation of Hα emission in the direction of infall, followed by a quick truncation of star formation (Gunn & Gott 1972, Tonnesen & Bryan 2010). A gentler mechanism, like 'strangulation', will remove just the hot gas reservoir around the galaxy leading to a gradual, spatially-uniform decline in the star formation rate (Larson et al. 1980, Balogh et al. 2000). Direct physical interactions with other galaxies, such as harassment or merging, will lead to disrupted, chaotic emission (Moore et al. 1999). Satellite-enhanced AGN feedback would lead to central concentrated, 'hard' line emission and large scale outflows (Harrison et al. 2012, McGee 2013). Critically, each of these mechanisms is expected to vary in effectiveness with the halo mass of the system.
At low redshift, progress has been stifled by the apparent lack of environmental imprint on the star forming population; dense environments are dominated by quiescent galaxies, but the star–forming population itself appears the same as in the field. This has given rise to the suggestion that galaxies experience a long 'delay' period after they become satellites, when their properties evolve as if they were field galaxies, followed by a rapid decline of star formation (Wetzel et al. 2012). Unfortunately, this means there are very few transforming galaxies in any population of low redshift star forming satellites. However, this does not appear to be the case at z $\sim$ 1, where star formation is proceeding more vigorously, and the fraction of satellites accreted into clusters per Gyr is more than triple that at z=0 (McGee et al. 2009). This, combined with our observations that satellites are efficiently quenched at this redshift (Muzzin et al. 2012, Mok et al. 2013), means that a large fraction of the star forming population should be actively undergoing morphological transformation and a quenching of star formation. **It is the aim of this proposal to undertake a detailed study of the transforming satellites in five galaxy systems at z = 0.8 — 0.9, spanning a range in halo mass.**

B – Immediate Objective: Our understanding of group and cluster galaxies at $z > 0$ has been limited by a lack of optical spectroscopy, needed to unambiguously identify members, and to establish dynamical masses for their haloes. We have recently completed the GEEC2 (Mok et al. 2013) and GCLASS (Muzzin et al. 2012) spectroscopic surveys of 11 groups and 10 clusters at $z \sim 1$. The foundation of these surveys are $> 300h$ of deep Gemini spectroscopy, from which redshifts and optical line diagnostics are available for hundreds of satellite galaxies in a wide range of halo masses at $0.8 < z < 1.3$. The GEEC2 groups lie in the COSMOS field and thus benefit from deep data from almost all major observatories. The GCLASS clusters, selected from the Spitzer Wide-area Extragalactic Survey (SWIRE), all have 11-band photometry from which accurate stellar masses have been determined (van der Burg et al. 2013), and MIPS imaging so the contribution from dust-obscured star formation can be quantified. These are the premier, multi-wavelength datasets on massive haloes at this redshift, and the spectroscopic investment will not be surpassed for some time to come. **This sample allows the most efficient use of KMOS and its unique capabilities to observe satellite galaxies at this epoch in a completely new way**.

Science Goals: We will observe five important emission lines (Hα, Hβ, [NII], [OI] and [OIII]) in a sample of $\sim$ 100 star forming satellite galaxies with $M > 10^{9.3} M_{\odot}$ at z $\sim$ 0.8 - 0.9. These galaxies are drawn from five groups/clusters, ranging in halo mass from $\sim 10^{13}$ to $> 10^{15} M_{\odot}$ (see Figure below) and located at a redshift where all key emission lines are easily measured from near-infrared spectroscopy. These observations will be made with KMOS in two setups, using the IZ passband for Hβ and [OIII], and the YJ band for Hα, [NII] and [OI]. By supplying these unique rest-frame optical emission lines, KMOS will allow us to address a wide range of science questions, including:

• **Precise Hα star formation rates** - Hα emission is the most sensitive, well-calibrated SFR indicator for galaxies with normal (or declining) SFRs, and is sensitive to nearly instantaneous ($\sim$ 10 Myr) star formation. Most analysis at $z > 0.5$ relies on rest-UV emission, which is very dust sensitive, and/or mid-IR emission, which is only sensitive to the highest SFR (e.g. see Figure below). With the advent of multi-object NIR spectrographs, it is finally possible to measure accurate SFR for many group and cluster galaxies at $z \sim 1$. We will correct for dust absorption using the Balmer decrement, (Hα/Hβ; see Kashino et al. 2013 for recent work using this technique at $z \sim 1.6$, using an inferior spectrograph). These measurements, when combined with the Spitzer MIPS and Herschel FIR data, will precisely determine the satellite star formation rates. Comparing these measurements to the well determined field galaxy star forming sequence will quantify exactly how star formation is affected in high redshift satellites.

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

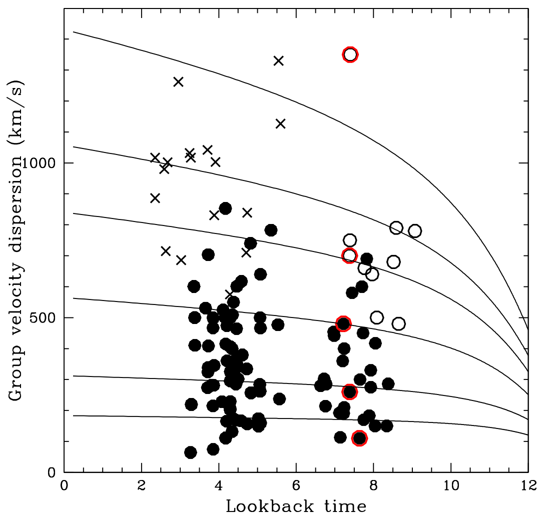
• **Spatial distribution of line emission** - The spatial distribution of the line emission is one of the best ways to distinguish between the variety of physical mechanisms that might quench star formation in satellite galaxies, and is efficiently obtainable with KMOS. For example, galaxy star formation may be truncated from the outside first, causing smaller, concentrated Hα emission (Abadi et al. 1999, Bekki & Couch 2010). Gentle mechanisms predict a uniform fading of the Hα emission (Balogh et al. 2000), while still more aggressive ones predict an elongation along the direction of the infalling galaxies (Kawata & Mulchaey 2008, Tonnesen & Bryan 2010). With KMOS, we expect $\sim$ 5 kpc spatial resolution, easily allowing the inner and outer parts of the galaxy emission to be separable.

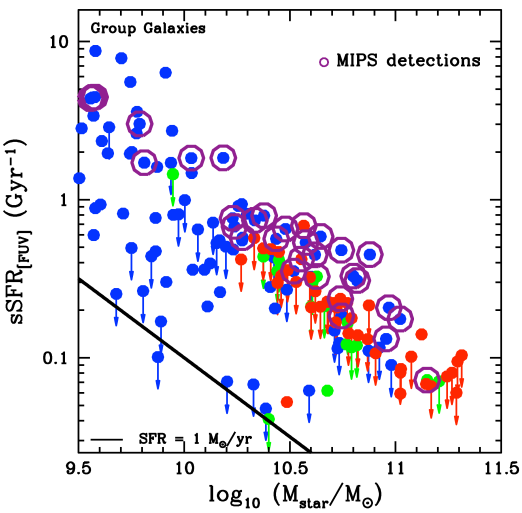
• **AGN Activity** - Feedback from active galactic nuclei are thought to play a key role in the quenching of star formation in massive galaxies. While it is clear that the influence of AGN increases at higher redshift (Martini et al. 2013), their effect on environment-specific quenching and on the contamination of star formation measures is poorly constrained, as the majority of high redshift AGN are found through rare, luminous X-ray emission. With our full complement of emission lines, we can identify low-luminosity galaxies using the BPT diagram used so effectively at low redshift (Baldwin etal. 1981; Trump et al. 2013) and recently extended to high redshift (Kewley et al. 2013ab). This will allow us to identify which galaxies host AGN, and how those AGN might have biased previous measurements of SFR; in those cases for which the Hα mission is broad, we can use the line width to estimate the mass of the black hole.

• **Mass-metallicity relation** - We will use the [NII]/Hα and ([OII]+[OIII])/Hα flux ratios as a probe of the galaxy metallicity (e.g. Henry et al. 2013) and the extensive photometry for robust measurements of the stellar mass. The location of satellite galaxies in the mass-metallicity (or mass-metallicity-sfr) plane is a powerful constraint on the baryon cycle in all galaxies (Davé et al. 2011, McGee et al. in prep). The relative lack of inflowing gas in satellite galaxies means that determining the metal content is a probe of the enrichment and strength of outflowing winds.

• **Large scale kinematics** - We expect to recover galaxy wide kinematics for many of these galaxies. This will be used to determine the degree to which these galaxies are rotation- or dispersion-dominated, as well as the degree of emission 'clumpiness' from mergers or other instabilities. Further, determining the v/σ value give a measure of the degree to which the cluster disks are turbulent.

The data from this proposal will make a large impact in the new science areas being opened by KMOS. For a modest investment of time, we will measure accurate physical parameters for $>$ 100 high redshift satellite galaxies. These measurements will serve as a baseline for future KMOS group and cluster science, and lead to the solution of a 3 decades old problem.





Left: To reconstruct the star formation history of satellite galaxies it is necessary to trace structure over a range of halo masses and redshifts. Lines indicate the predicted growth history of systems with present-day masses ranging from small groups (10^{13} M⊙) up to large clusters (5×10^{15}M⊙). Points show galaxy systems for which we have comprehensive optical spectroscopy: black filled points are the GEEC1 and GEEC2 groups (at low and high redshift, respectively) while the crosses and open circles are CNOC and GCLASS clusters, respectively. *The red circles identify the systems chosen for this project.* **Right:** The relation between sSFR and stellar mass, for GEEC2 group members. Here, SFR is estimated from the rest UV flux, and a highly uncertain dust correction. There are many upper limits because a small amount of dust obscuration has a dramatic effect on the UV flux. MIPS detections (purple circles) are limited to galaxies with the highest SFR. Blue, green and red points denote galaxies classified by their optical colours as star-forming, intermediate, or passive.

Refs: Abadi et al. 1999, MNRAS, 308, 947. Baldwin et al. 1981, PASP, 93, 5. Baldry et al. 2006, MNRAS 373, 469. Balogh et al. 2000, MNRAS, 540, 113. Bekki & Couch 2010, MNRAS, 408L, 11. Behroozi et al. 2013, ApJ 770, 57. Dave et al. 2011, 416, 1354. Dressler 1980, ApJ, 236, 351. Gunn & Gott, 1972, ApJ, 176, 1. Harrison et al. 2012, MNRAS, 426, 1073. Henry et al. 2013, arXiv1309.4458. Kawata & Mulchaey, 2008 ApJ, 672L, 103. Kashino et al. 2013, arXiv1309.4774. Kewley et al. 2013a, Apj, 774, 100. Kewley et al. 2013b, ApJ, 774, L10. Larson et al. 1980, ApJ, 237, 692. Martini et al. 2013, ApJ, 768, 1. McGee 2013, arXiv1302.6237. Mok et al. 2013, MNRAS, 431, 1090. Moore et al. 1996, Nature, 379, 613. Muzzin et al. 2012, ApJ,746, 188. Muzzin et al. 2009. ApJ, 698, 1934. Patel et al. 2013, arXiv1304.2395. Peng et al. 2010, ApJ 721, 193. Trump et al. 2013, ApJ, 763L, 6. van der Burg et al. 2013, A&A, 557.15. Wilson et al. 2009 ApJ, 698, 1943. Weinmann et al. 2006, MNRAS, 366, 2. Wetzel et al. 2013, MNRAS 432, 336

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: In the near infrared the moon does not substantially increase the continuum level of the sky background and as such we do not need to request dark time. As mentioned in the KMOS manual, we should avoid observing closer than 30^o to the Moon to minimize telescope guiding problems.

Time Justification: (including seeing overhead)

The KMOS field of view is comparable to the fields over which we have obtained optical spectroscopy in each group or cluster, and we will be able to place all IFUs on targets with known redshifts. Priority will be given to those for which we expect strong emission (i.e. those with blue rest-frame colours and/or [OII] emission). We have selected groups and clusters at redshifts where all five target emission lines lie at wavelengths with good atmospheric transmission and minimal contamination from sky emission lines.

We aim to spatially resolve the stronger emission lines and measure integrated measurements for the weaker lines. Using the KMOS ETC, we find that, in 2400s exposure with the YJ filter, each resolution element of 1.0 arcsec^2 will detect emission of 2×10^{-17} erg/s/cm^2 at 3σ. For a typical dust obscuration of ~ 1 mag, this emission in Hα at $z \sim 0.85$ corresponds to a SFR $\sim 1.5 M_{\odot}$/yr, which reaches well below the star-forming "main sequence" for our sample of $M_{*} > 10^{9.3} M_{\odot}$ galaxies (see Figure). Typical galaxies on this main sequence are expected to have SFR of 4–8 M$_{\odot}$/yr (Muzzin et al. 2012), and these will be detected with $> 7\sigma$ significance. For galaxies with larger than average SFR, we will easily be able to resolve the emission spatially.

For galaxies dominated by AGN activity, the [NII] emission is at least as large as the Hα, and will therefore be detectable at the limit of our survey. The IZ filter pointings will be aimed at detecting Hβ and [OIII]. In star forming galaxies at this redshift, the [OIII] emission is on the order of the strength of the Hα emission (Dominguez et al. 2012). We can detect Hβ or [OIII] emission of 6×10^{-17} erg/s/cm^2 at 5σ significance in a 1.4 arcsec^2 resolution element during 3000 seconds of on source time. In a similar time, we will be able to detect 3×10^{-17} erg/s/cm^2 integrated across the source at the 5σ level. The unextincted ratio of Hα/Hβ is $\sim$ 2.7, with this ratio becoming greater with increasing extinction. For 1 magnitude of dust, assuming a Cardelli et al. (1989) dust law, this is 4.4. For the majority of our sources, H$\alpha > 10^{-16}$ erg/s/cm^2 and we will be able to measure the integrated Balmer decrement (e.g. Kashino et al. 2013).

We will use the 'stare' observing mode, in which a small number ($\sim$ 2-3) of IFUs are used to continually monitor the sky. The variations between pickoff arms are calibrated by infrequent dedicated sky positions where all the IFUs observe the blank sky. The sky subtraction is done by correcting the continual measure of the sky to the response of the individual IFU. Given the expected overheads of 10-12 mins per setup, we require 1.4 hour for each YJ pointing and 1.6 hours for each IZ pointing.

8a. Telescope Justification:

The KMOS instrument is unique in the world. It is the only instrument which allows multiple IFU spectral images of near infrared objects to be taken at once. As such, it is perfectly suited to observe Hα in galaxy groups and clusters at $z = 0.9$. The unique processes ongoing in these systems may be imprinted on the spatial distribution of the Hα emission. Our extensive spectroscopic campaign has identified 45 members in each cluster and $\sim$ 20 members in each group, of which about half are [OII] emitters. We expect to fill most of the KMOS IFUs with these confirmed emitters, several on possible emitters and with a small number devoted to observing the sky. We note that studies of galaxy groups and clusters at high redshift were a key driver of the KMOS science case, and our proposal contains the optimal systems for efficient use of KMOS.

8b. Observing Mode Justification (visitor or service):

While we would welcome visitor time, the narrow RA range of each of our groups and clusters makes them inefficient to observe in full nights. With this in mind, we request service mode observations.

8c. Calibration Request:

Standard Calibration

9. Report on the use of ESO facilities during the last 2 years

"The timescale of environmental change: Hα imaging of galaxy groups at z=0.4", Run 091.B-0613, PI: McGee. Only 20% of the data has been taken. It will be combined with additional data.

9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

There is no such data in the archive. KMOS is a new instrument with unique capabilities and no similar existing instrument exists.

9b. GTO/Public Survey Duplications:

Two of our fields are in the COSMOS survey region. We have confirmed that our targets are *not* targets of the GTO programme in that field. Thus, there is no duplication.

10. Applicant's publications related to the subject of this application during the last 2 years

McGee, S. 2013, MNRAS, in press, (arXiv:1302.6237) - "The strong environmental dependence of black hole scaling relations".

Noble, A.G., Webb, T., Muzzin, A., Wilson, G. et al. 2013, MNRAS, in press: "A kinematic Approach to Assessing Environmental Effects: Star-Forming Galaxies in a z$\sim$0.9 SpARCS cluster using Spitzer 24μm Observations"

Bahé, Y, McCarthy, I, Balogh, M, et al. 2013, MNRAS, in press: "Why does the environmental influence on group and cluster galaxies extend beyond the virial radius?"

van der Burg, R., Muzzin, A., Hoekstra, H., Lidman, C., et al. 2013, A&A, 557. 15.

Lidman, c., Suherli, J., Muzzin, A., Wilson, G. et al., 2012, MNRAS, 427, 550L: "Evidence for significant growth in the stellar mass of brightest cluster galaxies over the past 10 billion years"

Mok, A., Balogh, M., McGee, S. et al. 2013, MNRAS, in press: "Effcient satellite quenching at z=1 from the GEEC2 spectroscopic survey of galaxy groups".

Hou, A., Parker, L. et al. 2012, MNRAS, 421, 3594. "Substructure in the most massive GEEC groups: eld-like populations in dynamically active groups"

Lu, T., Gilbank, D., McGee, S., Balogh, M., et al. MNRAS, 420, 126. "CFHT Legacy Ultraviolet Extension (CLUE): witnessing galaxy transformations up to 7 Mpc from rich cluster cores"

Muzzin, A., Wilson, G. et al, 2012, ApJ, 746, 188. "The Gemini Cluster Astrophysics Spectroscopic Survey (GCLASS): The Role of Environment and Self-Regulation in Galaxy Evolution at z$\sim$ 1"

McGee, S., Balogh, M. et al. 2011, MNRAS, 413, 996. "The Dawn of the Red: Star formation histories of group galaxies over the past 5 billion years".

Balogh, M., McGee, S. et al. 2011. MNRAS, 412, 2303, "Direct observational evidence for a large transient galaxy population in groups at $0.85 < z < 1.0$"

Balogh, M et al. 2011, MNRAS, 412, 947, "The stellar and hot gas content of low-mass galaxy clusters"

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	SpARCS Cluster 1	00 34 42.1	-43 07 53.3	1.3	21		$z = 0.867$	
B	SpARCS Cluster 1	00 34 42.1	-43 07 53.3	1.6	21		$z = 0.867$	
C	SpARCS Cluster 2	00 36 45.1	-44 10 49.9	1.3	21		$z = 0.869$	
D	SpARCS Cluster 2	00 36 45.1	-44 10 49.9	1.6	21		$z = 0.869$	
E	GEEC2 213/213a	10 01 38.4	+02 30 43.2	1.3	21		$z = 0.879$ & 0.9256	
F	GEEC2 213/213a	10 01 38.4	+02 30 43.2	1.6	21		$z = 0.879$ & 0.9256	
G	GEEC2 120	10 02 1.2	+02 13 30.5	1.3	21		$z = 0.8358$	
H	GEEC2 120	10 02 1.2	+02 13 30.5	1.6	21		$z = 0.8358$	

Target Notes: These are galaxy groups and clusters with known redshifts from deep optical spectroscopy at z =0.8 — 0.9. We will primarily target the star forming members of these systems. NIR magnitudes are typically $<$ 21 AB. Two of the groups (231 and 231a) are spatially coincident. Thus the two clusters and three groups can be covered in four KMOS fields.

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
93	KMOS	A	IFU	YJ
93	KMOS	B	IFU	IZ
93	KMOS	C	IFU	YJ
93	KMOS	D	IFU	IZ
93	KMOS	E	IFU	YJ
93	KMOS	F	IFU	IZ
93	KMOS	G	IFU	YJ
93	KMOS	H	IFU	IZ

6b. Co-investigators:

...continued from Box 6a.

A.	Finoguenov	Helsingin yliopisto,FI
G.	Wilson	Department of Physics and Astronomy,University of California Riverside,US
H.K.C.	Yee	University of Toronto,Department of Astronomy and Astrophysics,CA
A	Mok	McMaster University,Department of Physics and Astronomy,CA
C.	Lidman	Australian Astronomical Observatory,AU