Galaxies Under the Cosmic Microscope: A Preview to ELT science

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Galaxy formation is a complex process:
- cold diffuse gas inside dark matter halo
- gas heated by gravitational collapse
- cooling via X-ray emission
- condensing of gas into stars forming a disk which is supported by angular momentum
- feedback by stellar winds and supernova
- merging of galaxies to build up halo and stellar mass

Understanding Galaxy Evolution

How did the galaxies in the local Universe form and evolve?
- Redshift surveys have shown that galaxy formation was much more efficient at high-z.

- Most of today's "normal" galaxies were being assembled at z=1-5.

- What are the properties of galaxies at these early times:
  - Dynamical state?
  - Distribution of SF?
  - Gas Masses, SFEs?
  - Gas dynamics?
  - Interaction between SF and gas dynamics?
  - Chemical Abundances?
What we need is a way to spatially resolve distant galaxies. ...then we could figure out the dynamics, distribution of SF, scale, energy and mass involved in outflows.

Key Questions:
- What are dynamics? $v_{\text{rot}}$, $\sigma$, M/L ratio?
- Do galaxies form inside out or outside in?
- How much energy & mass do the super-winds have?
- Will outflows escape the galaxy? How far do they travel?

But, the sizes and flux scales involved make it incredibly difficult to spatially resolve the dynamics and SF properties of star-forming galaxies at high-z.
- Significant population of "normal" galaxies at \( z \sim 3 \) identified are LBGs.

- Actively SF, low dust, dynamical/stellar masses and chemical properties expected for local spirals/spheroidals.
Identifying high-redshift galaxy populations

- Actively SF, low dust, dynamical/stellar masses, chemical properties and space densities expected for local spirals/spheroidals

- Responsible for ~30-40% of the cosmic SF history between z=2-3

  e.g. Shapley et al. 2003, 2006, Erb et al. 2004

\[ \text{SFR} \sim 20 \, \text{M}_\odot/\text{yr} \]

\[ M^* \sim 4 \times 10^{10} \, \text{M}_\odot \]

\[ L_{\text{bol}} \sim 10^{11.5} \, L_\odot \]

\[ M_{\text{dyn}} \sim 7 \times 10^{10} \, \text{M}_\odot \]
Forster-Schreiber et al. (2006) studied 14 LBGs with SINFONI and found evidence for rotation on ~4kpc scales and velocity shears in 9/14 and rotation in 3 galaxies.
Most studies have mapped the demographics of the population as a whole. What is needed is detailed studies of individual galaxies.

Genzel et al. 2006 studied unusually large object at z=3 on ~1kpc (0.1") scales and found evidence for rotation.
Near-IR Diffraction limits

- Starburst region
- Giant HII region
- Compact HII region
- Globular cluster

Dimensions:
- 8m
- 40m
- 100m

Wavelength (microns) vs Angular size (arcsec)
The Problem:
- HII regions have characteristic sizes of ~50pc
- distant galaxies are faint!
- dispersed light loses contrast (sky noise, flat field errors), read-noise, dark current (in near-IR)
- distant galaxies are small
  (AO correction is not magic!)
Observing Galaxies in the Distant Universe

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IFU observations of young galaxies are extremely challenging!
The Answer: Use a BIG telescope!

10^{21} m primary with an 8m secondary

Gravitational Telescopes:
- Lensed Galaxies are much brighter
- AND much bigger

"Galaxies Under the Cosmic Microscope"
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JWST

Angular size (arcsec)

Wavelength (microns)

8m
40m
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Mass modelling and source plane reconstruction
Example: Abell 2218 arc#289

Original image → Galaxy Cluster → Lens model

The 3D view:

Unlensed Image

Swinbank et al. 2003, 2006
Extremely Detailed Studies: example of detailed study of lensed L* LBG at z=3

$L_K = 22.6 \pm 0.2$ (AB), $M_K = -22.2 \pm 0.2$ ($\sim L_K^*$)
SFR $\sim 100 \, M_\odot$yr$^{-1}$
Masses: $1 \times 10^{10} M_\odot$ (dynamics)
    $7 \times 10^9 M_\odot$ (stellar)
    $5 \times 10^8 M_\odot$ (gas)
Timescale = Gas mass/SFR = 40Myr!
Keck/OSIRIS LGS (Sept 2007). LGS delivers 0.075” resolution (100pc in source plane!)

HST/ACS images

Datacube Projection
Each pixel in 100pc and independent: Resolution is 10mas in non-lensed case!

\[ M_{\text{dyn}} \approx 6 \times 10^9 M_\odot \text{ (R<1.8kpc)} \]

\[ \Sigma_{SFR} = 4.4 M_\odot/\text{yr/kpc}^2 \]

\[ v/\sigma = 1 \text{ (thick disk)} \]
Synergies with other facilities: eg. ALMA

Predicted location of CO

Predicted FWHM of CO

First Constraints on $\alpha$ at high-z:

$$M(H_2) = \alpha L'_{CO}$$

Since gas mass MUST to be less than dynamical mass suggests $\alpha < 0.8$
Push to higher-$z$:
Quick example: RCS0224-002 $z_{cl}=0.78$

$I=25.2$ (source plane) ... an $L^*$ galaxy at $z=5$

$z=4.88$ arc
Reconstructed images of the z=4.88 arc

Reconstructed image (HST VI-band)
Amplification = 16 (Δm = 3.0 mags)

SFR = 12+/-2 M☉/yr
Putting the OII, Ly$\alpha$ and UV-ISM diagnostics together

Based on Tenorio-Tagle et al
Physics of high-z galaxies
First light galaxies with ELT
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First light galaxies with ELT
What I want you to remember

As the spatial resolution of observations increases, galaxy dynamics appear increasingly complex -- continually pushing the limits -- sub-kpc in UV samples and now achieving ~few 100pc in best lensed examples.

Strong lensing allows us to probe ELT science a decade ahead of its time, albeit in only a handful of galaxies.

ELT EAGLE has the opportunity to build samples of 1000s(?) of high-z (z~2) galaxies on scales of ~100's parsecs (field+cluster case).

ELT HARMONI has opportunity to follow-up best examples on scales of ~50pc (and <10pc in lensed case).

What is the ubiquity of first galaxies?
What are their stellar populations?
What was their role in reionisation?

What is the relative contribution of Pop II and III stars
What is the interaction between SF and gas?
How rapidly did reionisation occur?
What I want you to remember

Strong lensing allows us to probe ELT science a decade ahead of its time, albeit in only a handful of galaxies.

- Now able to derive structural parameters, distribution of SF, interaction of SF and gas and measure energetics of feedback in best cases on ~100pc scales
- Lensing also allows us to target molecular content of "normal" galaxies to derive gas mass, depletion timescale and relation between CO mass and total gas mass reservoir (ALMA)

 Increased light grasp and resolution will make these studies common-place.

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- ELT HARMONI has opportunity to follow-up best examples on scales of ~50pc (and <10pc in lensed case).
In both the lensed and non-lensed case, ELT will probe the physics of galaxies within the epoch of reionisation.

What is the ubiquity of first galaxies?

What are their stellar populations?

What was their role in reionisation?

What is the relative contribution of Pop II and III stars?

What is the interaction between SF and gas?

How rapidly did reionisation occur?