KMOS^{3D} reveals low-level star formation activity in massive quiescent galaxies at $0.7 < z < 2.7$

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Contents

Abstract

Hα emission in the massive quiescent galaxies observed by KMOS3D
→ Robustly detected 20 out of 120 UVJ-selected quiescent galaxies

To classify the emission mechanism, use the Hα line width and [NII]/Hα ratio
→ AGN are responsible in more than half of the case
Star formation activity in 9 quiescent galaxies

For 9 galaxies with star formation activity

- Hα kinematics reveal rotating disk in 5 of the 9 galaxies
- Dust-corrected Hα star formation rate are low (0.2 – 7 $M_\odot$/yr), below MS
- 24μm-based IR luminosity overestimate the SFR
- Lower gas-phase metallicity than star-forming object with similar stellar mass
- Many of them have close companion

→ Their star formation activities are fueled by **inflowing gas** or **minor merger,** and could be **a sign of rejuvenation events**

1. Introduction

Massive quiescent galaxies at high redshifts (e.g. Franx+2003, etc.)

- Rapid assembly of stellar mass and sudden quenching
- How star formation remains quenched
    - Low-level feed back from AGN
    - Stellar winds from old stars
    - gravitational heating

→ One of the key prediction of models is the level of residual star formation

Massive quiescent galaxies have been studied via …

- Photometric data (Fitting the observed SED)
  → Less reliable for SFR, particularly for low level SFR or affected by dust extinction
- Infrared emission by dust
  → Unknown contribution of different sources to the heating of dust

→ Measuring star formation activity with Hα emission

→ The large and deep sample of $KMOS^{3D}$

2. Data

KMOS^{3D}

- 2″.8 x 2″.8 near-infrared integral field units
- Three of CANDELS field (a wealth of ancillary data are available)
  → Stellar mass, dust extinction, and rest-frame color with Wuyts+2011 method
- $0.7 < z < 1.1$, $1.3 < z < 1.7$, $1.9 < z < 2.7$ from prior spec-z/grism-z
- magnitude cut $Ks < 23$
  → 95% mass-completeness: $\log(M^*/M_\odot) \sim 9.7, 10.2, 10.5$ for each z-bins
  → diverse target sample spanning a wide range in masses, environments, sizes, colors, and star formation rates
- natural seeing: 0″.4-0″.8 FWHM (median 0″.53)
- Spectral resolution σ~25-50 km/s
- Exposure time = 4-25 hours

→ **This paper includes 560 galaxies observed in the first 3 years of the survey**

Extract a 1D spectrum by coadding the spaxels associated with the galaxies
→ 399 robust Hα detections, with $S/N > 3$ and no strong contamination from sky lines
(For resolved object, extract a velocity-corrected spectrum)

3. Hα emission in quiescent galaxies

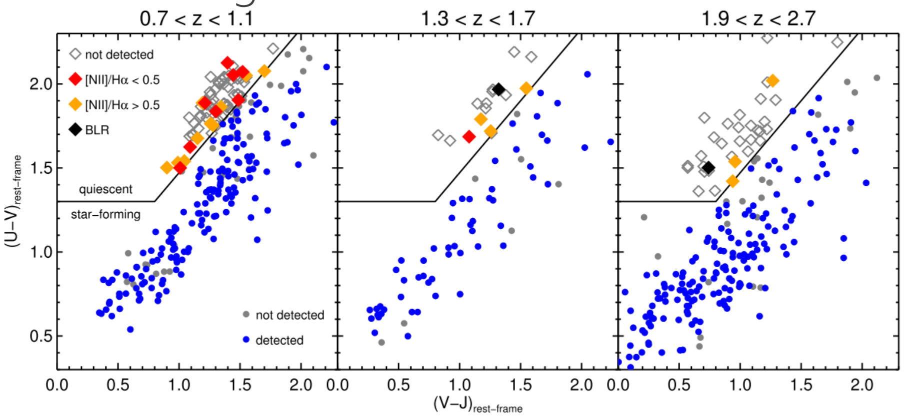
Quiescent galaxies are selected by rest-UVJ color diagram

- Remarkably effective even when dust reddening is present (e.g. Wuyts+2007)
- Criteria of Muzzin+2013, without the V-J < 1.5
  → Don’t exclude very red quiescent systems (e.g. van der Wel+2014)

Hα detection rate

- Star-forming galaxies: 86%
- UVJ-quiescent galaxies: 20/120 → 17%
  - Including 13 marginal or contaminated detection → 27%
  - Most of them happen to lie near the edge of UVJ-selection box

Fig 1.



3. Hα emission in quiescent galaxies

Emission line property variation among the 20 quiescent galaxies
to find star formation activity in them

- 2 cases: broad Hα (σ~500-1000 km/s) & no [NII]: Broad line region around BH
  → Also detected in the X-rays and excluded from further analysis

→ Split remaining objects into 2 subsamples according to [NII]/Hα
→ Discriminate between star formation ([NII]/Hα<0.5 (Kewley+2013)) and others

- 9 galaxies: weak or non-detected [NII] emission ([NII]/Hα<0.5) → [NII]-weak
- 9 galaxies: [NII]/Hα>0.5 → [NII]-strong

Additional 13 galaxies with marginally or contaminated detection: 6 [NII]-weak

3. Hα emission
in quiescent galaxies

WHAN diagram (Hα EW vs [NII]/Hα) (Cid Fernandes+2011)

- [NII]-weak galaxies populate the star formation
- Lower-limit of Hα, EW > 3A, has been proposed in local universe (Cid Fernandes+2011, Belfiore+2016)

Intrinsic σ vs [NII]/Hα diagram

- Larger σ at higher [NII]/Hα → Presence of shocks
- [NII]-weak quiescent galaxies have smaller σ
  Not due to a difference in stellar mass

Stacked spectra

- σ of [NII]-weak quiescent
  → similar to star forming
  smaller than [NII]-strong

[NII]-strong & σ trend with [NII]/Hα
→ large-scale outflows by AGN
(Förster Schreiber+2014
Genzel+2014)

Fig 3.

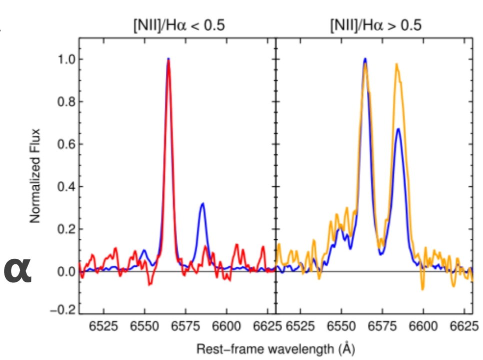
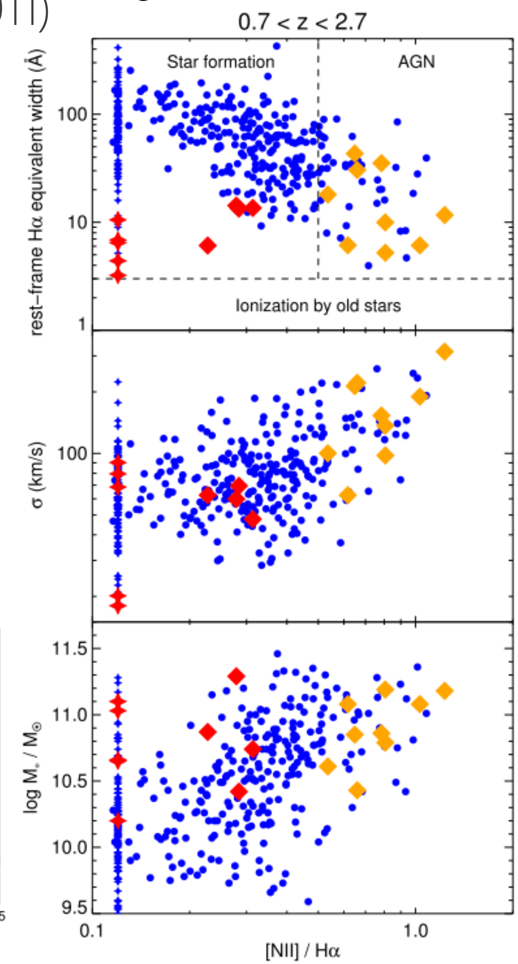


Fig 2.



4. Star formation in quiescent galaxies

4.1. Rest-frame Colors

- All the quiescent star-forming galaxies (except COS4-03894) lie around the edge of red sequence in UVJ diagram
- Most of them are found in extremities of the red sequence
  - 3 of them have very blue colors (U-V~1.6): young age about 1 Gyr
  - 3 of them have red colors (U-V~2.1): old stellar age and dust reddening

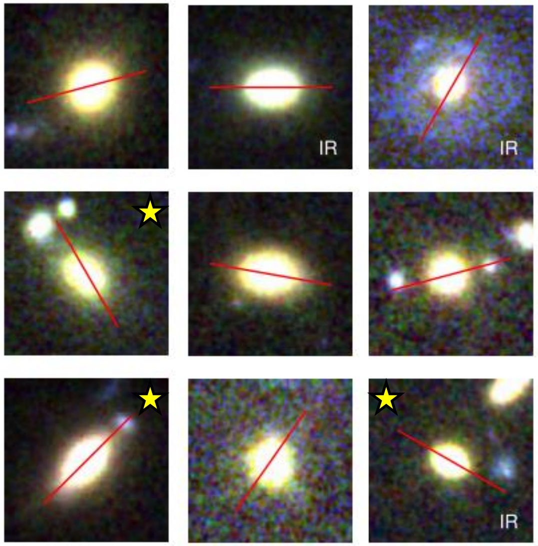
4.2. Morphology and Environment

- Many have one or more companions
  - In KMOS^{3D} datacube, within 800km/s (with yellow star mark)
  - In 3D-HST catalog, within 50kpc and 1σ redshift errors

→ 7 of 9 [NII]-weak galaxies have low-mass companions

No correlation with the local overdensity

Fig 4. HST images (4″x4″ for *IJH*-band)

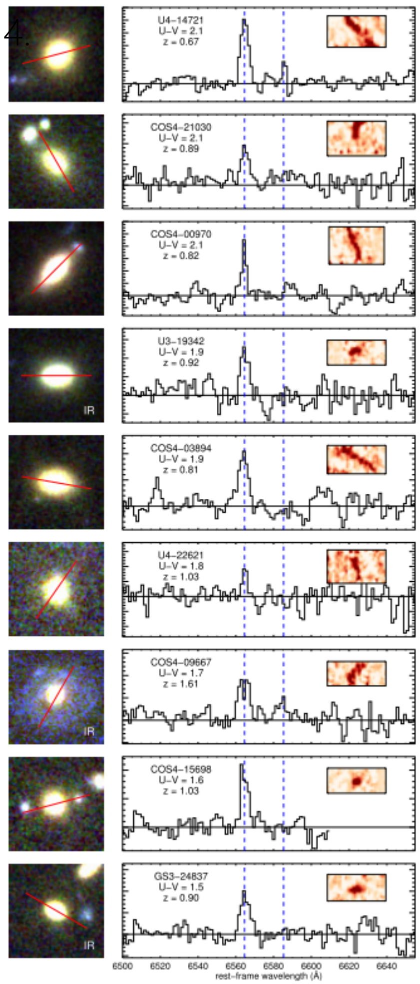


4. Star formation in quiescent galaxies

4.3. Kinematics

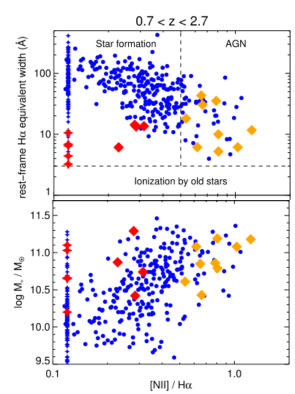
- 5 of 9 galaxies are resolved
  and show smooth velocity gradient → gas disk (> 4 kpc)
- Rotational veleocities: 100-200 km/s
  Exception: COS4-03894 ~400 km/s
- Velocity dispersion: 50-270 km/s (median 103 km/s)
  → smaller than typical stellar value (150-300 km/s)
  → gas and stars have different distributions

Fig 4.
Fig 4.



4.4. Gas Metallicity

- [NII]/Hα method ([NII]/Hα↗, Metallicity ↗)
- lower [NII]/Hα at fixed Hα EW and
  stellar mass compared to SFG
  → Ionized gas in the quiescent galaxies
  is more metal-poor



4. Star formation in quiescent galaxies

4.5. Star Formation Rate

Dust-corrected Hα SFR (Kennicutt+1998 & Chabrier2003 & Wuyts+2013)
→ 0.2-7 $M_\odot$/yr , mean~1.5 $M_\odot$/yr

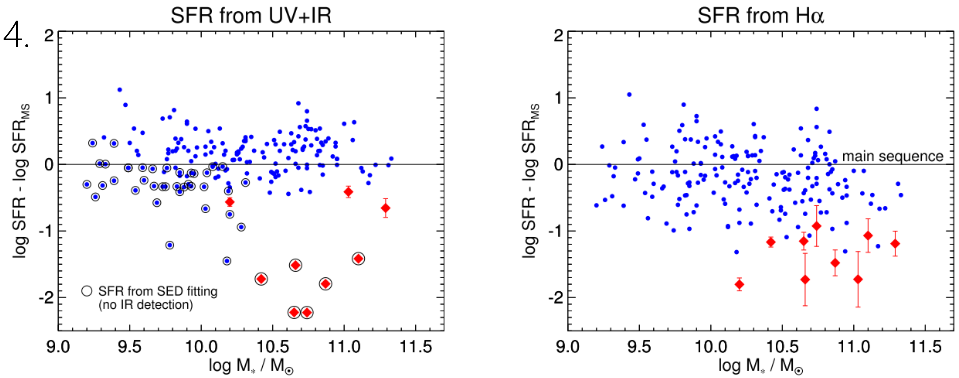
$$\mathrm{SFR}_{\mathrm{H}\alpha} = 4.65 \times 10^{-42} L_{\mathrm{H}\alpha} 10^{-0.4A_{\mathrm{extra}}} 10^{-0.4A_{\mathrm{cont}}}$$

Comparison with SFR(UV+IR)

- For quiescent galaxies detected in the IR, UV+IR method can overestimate the SFR
  ← Old stellar population can significantly contribute to the dust-heating
  (photometric studies: Utomo+2014, etc., numerical simulation: Hayward+2014)
- IR detections are anticorrelated with dust extinction and U-V color
  → Reddest galaxies are not hosting dust-obscured star formation
- Hα MS is broader
  ← Shorter timescales probed by Hα
  - burstiness

  → More continuous distribution with quiescent population

Fig 4.



5. Discussion

Rejuvenation event triggered by interactions with gas-rich, low-mass and lower-metallicity system

However, they can still be quiescent

- An average increase of stellar mass of the star formation < 10% from z~1 to 0 (Assuming constant SFR → Upper limit)

In the recent past of rejuvenation, these objects

- were already passively evolving
- have not yet been completely quiescent but were undergoing quenching

→ Strength of rejuvenation is different (Stronger in the former case)

→ Unveil by a detail analysis of their star formation history

Large gas disks

→ scenario in which rotation plays important role in all stages of galaxy evolution at high redshift

Compact SFG rotating ionized gas → QG in this sample still keep rotating gas → Gas-poor QG rotating stellar kinematics