A KCWI study of Lya nebulae in high redshift clusters

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Subaru 20
Back in 2016: surprise: a Lya nebula, over the cluster core

Valentino et al. 2016
Cold gas co-existing with hot gas

Valentino et al 2016

Cold $10^4$ K plasma

Hot $10^7$ K plasma
Cold accretion required from understanding of SFR evolution

Galaxies have gas consumption times $\sim$0.5-1 Gyr but keep going for x10 longer

→ Need fueling and replenishment, otherwise cannot work

→ Postulate ‘cold flows’ accretion to maintain the ‘steady state’

(predicted by theory, never convincingly/definitively observed so far)


Rodsahl & Blaizot 2012
Cluster environment a place to search for lyman alpha nebulae. However...

- Nearly all giant lyman alpha nebulae are known to be associated with high redshift quasars (e.g. Cantalupo et al.)
- The QSO provides the source of photoionization

- As member of Keck Cosmic Web imager science team, seeking out exciting science for KCWI
- Emanuele Daddi notes that MUSE cannot go blueward of 4500A; - an opportunity
- Observations in 2018 January and 2019 February
Keck Cosmic Web Imager is an integral field unit
<table>
<thead>
<tr>
<th>Instrument Configuration</th>
<th>Large</th>
<th>Medium</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Science Objective</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field of view</td>
<td>Large 33&quot; x 20&quot; Medium 16&quot; x 20&quot; Small 8&quot; x 20&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>Small: 4R0 Medium: 2R0 Large: R0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spatial sampling</td>
<td>Small 0.35&quot; Medium 0.70&quot; Large 1.35&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandpass (Instantaneous)</td>
<td>BL ~ 2000Å BM ~ 850Å BH ~ 400Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Surface Brightness</td>
<td>Large smaller is best [more sky around object, faster sky measurement] Small smaller is worst</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extended Emission</td>
<td>If emission line then best sensitivity when line is resolved.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity &amp; Sky</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtraction Accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>BL has best efficiency, BM close, BH slightly lower but comparable except for BH3</td>
<td></td>
<td></td>
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</table>

### Grating Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Large</th>
<th>Medium</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of View</td>
<td>33&quot; x 20.4&quot;</td>
<td>16.5&quot; x 20.4&quot;</td>
<td>8.4&quot; x 20.4&quot;</td>
</tr>
<tr>
<td>Slice width</td>
<td>1.35&quot;</td>
<td>0.69&quot;</td>
<td>0.35&quot;</td>
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<tr>
<td>Bandpass/Dispersion</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>BL</td>
<td>R (central) 0.625Å/pixel</td>
<td>900</td>
<td>1800</td>
</tr>
<tr>
<td>Delta (total)</td>
<td>350-560 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta (instantaneous)</td>
<td>200 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta (NAS)</td>
<td>50 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BM</td>
<td>R (central) 0.28Å/pixel</td>
<td>2000</td>
<td>4000</td>
</tr>
<tr>
<td>Delta (total)</td>
<td>350-550 nm</td>
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</tr>
<tr>
<td>Delta (instantaneous)</td>
<td>80-90 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta (NAS)</td>
<td>20-22 nm</td>
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<td></td>
</tr>
<tr>
<td>BH3</td>
<td>R (central) 0.125Å/pixel</td>
<td>4500</td>
<td>9000</td>
</tr>
<tr>
<td>Delta (total)</td>
<td>470-560 nm</td>
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<td></td>
</tr>
<tr>
<td>Delta (instantaneous)</td>
<td>47-53 nm</td>
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<tr>
<td>Delta (NAS)</td>
<td>12 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BH2</td>
<td>R (central) 0.125Å/pixel</td>
<td>4500</td>
<td>9000</td>
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<tr>
<td>Delta (total)</td>
<td>400-480 nm</td>
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<td></td>
</tr>
<tr>
<td>Delta (instantaneous)</td>
<td>37-44 nm</td>
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<td></td>
</tr>
<tr>
<td>Delta (NAS)</td>
<td>10 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BH1</td>
<td>R (central) 900</td>
<td>4500</td>
<td>9000</td>
</tr>
<tr>
<td>Delta (total)</td>
<td>350-410 nm</td>
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<td></td>
</tr>
<tr>
<td>Delta (instantaneous)</td>
<td>~40 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta (NAS)</td>
<td>~10 nm</td>
<td></td>
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</tr>
</tbody>
</table>
KCWI extends reach to $z=2$ by getting the blue

- MUSE cutoff about 4700 Å
- $z>2.9$
- KCWI especially efficient in blue, reaches $z=1.7$
- KCRM on the way; will reach to 1µm
New KCWI results (Daddi, Valentino, Rich et al. 2018)  R01001 z=2.9 (COSMOS field)

More Successful Detections of 6/7 clusters

FV_X  z=2.18
Strazz2 z=2.51
R1001  z=2.91
R0958  z=3.04
R0959  z=3.09
Wang   z=2.50

and also

Gobat cluster at 14h50 +09 z=1.99
RO-1001 nebula at z=2.91 No powering AGN identified

Figure 2: Lyα flux map (i.e., moment 0) of the RO-1001 nebula, reconstructed from adaptive smoothing. Three quite clear filaments/strems are detected outwards of the central bright core. The color bar at the bottom shows the Lyα surface brightness scale (SB), ranging from a few $10^{-17}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ at the center to 10× lower SB in the filaments. The field of view shown is the same in all figures. The red rectangle shows the GMOS IFU field.
RO-1001  z=2.91  $10^{13}$ Msun  possible cosmological cold flows

**Figure 1**: Deep imaging of the RO-1001 cluster from ULTRA-Vista K and J (red and green) and Subaru HSC g-band (blue). The 5 massive $>10^{11}M_\odot$ galaxies are labeled. The white contours show the Lyα surface brightness scale (SB) from Figure 2, from a few $10^{-17}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ (center) to x10 lower SB (filaments). Arrows show stream directions.
Kinematics from centroids of Lya peak velocities

Thanks to A. Marchal et al 2019

ROSHA code → 2D
Figure 3: Velocity (moment 1, left) and velocity dispersion (moment 2, right) maps of the RO-1001 nebula. The color bars at the bottom show the velocity scales in km s$^{-1}$. The white contours show the Lyα SB levels from Figure 2.
Lya nebula sitting at the center
Of the potential well of massive halo

$M_{\text{DM}} \sim 4 \times 10^{13} \text{Msun} \ @ z=2.91$

1) Stellar mass content 
2) SFR integrated (Herschel, ALMA) 
3) 3$\sigma$ X-ray detection 

$10^{11} \text{Msun} \ \text{HI by modeling L alpha emission (phase I SKA detectable)}$

$1200 \text{Msun/yr of SFR}$
RO-1001 falls in the cosmological cold flow regime
What is the source of the ionization? Photons?

ALMA half light radii ~500pc

No sign of AGN from IR

No X-ray AGNs
(soft/hard)
Lx<5x10^43 from 8-40keV rest

No way to get enough ionizing photons

AGNs weak if any, and VERY obscured
SF extremely obscured

Diffuse SF/AGN in many objects rejected from EW (no continuum), unlike Spider Web z=2.1
### RO-1001 vs QSO nebulae

Lya $\sim 2 \times 10^{44}$ erg/s

<table>
<thead>
<tr>
<th>Energy source</th>
<th>RO-1001 nebula</th>
<th>QSO nebulae</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Constrain</td>
<td>Total</td>
</tr>
<tr>
<td>AGN photo.</td>
<td>$L_{AGN} \lesssim 2 \times 10^{48} \text{erg s}^{-1}$</td>
<td>$\lesssim 60%$</td>
</tr>
<tr>
<td>SF photo.</td>
<td>1200$M_\odot \text{yr}^{-1}$</td>
<td>5</td>
</tr>
<tr>
<td>AGN outflows</td>
<td>$\lesssim 200 M_\odot \text{yr}^{-1}$</td>
<td>30%</td>
</tr>
<tr>
<td>SF outflows</td>
<td>1200$M_\odot \text{yr}^{-1}$</td>
<td>1</td>
</tr>
<tr>
<td>Gravity</td>
<td>$M_{DM} = 4 \times 10^{13} M_\odot$</td>
<td>160</td>
</tr>
</tbody>
</table>

1) Energy source, gravity vs photoionization? 4 orders of mag difference

2) Where is cold gas from, infall or outflows? >2 orders of mag difference
Comparing to Rosdhal & Blaizot 2012 simulations (see also Goerdt+2010)

- Luminosity
- SB distribution
- Area
- 3 filaments
- Velocities
- Column density

All informed with $\text{M}_{\text{DM}}$ knowledge

→ Excellent quantit. agreement with predictions
More where that came from!
The highest redshift ‘passive galaxy selected’ cluster from Strazzullo et al 2015

We initially thought it was $z \sim 2.19$, but KCWI shows a giant nebula at 2.51 again.

Lya image from Keck KCWI observations
Figure 2: Left: The most distant X-ray detected cluster known so far at $z = 2.506$ (Wang+2016). White and red arrows mark spectroscopic and photometric members, respectively. Right: A very strong concentration of red, strongly star-forming galaxies (total SFR$\approx 3400$ M$\odot$ yr$^{-1}$) is evident in the central 80 kpc. White and yellow lines mark the ALMA 870 $\mu$m and Chandra X-ray contours.
Wang et al 2016 $z=2.51$ cluster

Keck KCWI observations
Collaboration with Mike Rich
@UCLA

Lya image from Keck KCWI observations
A radio selected cluster $z=3.1$

Lya image from Keck KCWI observations
R0958  Red=radio  ALMA galaxy 600 Msun/yr SF  z=3.046  Ly Alpha 10x weaker. Lower mass halo?
Future Work

• ALMA observations just completed
• HST time in WFC3/IR allocated
• KCRM or MUSE to detect CIV, CII, He lines
• Gemini IFU under consideration
Conclusions

• LAN detected in 6/7 cases; more processing will probably find all
• Associated with radio overdensities and in some cases, no AGN so source of photoionization not known.
• Note that these are distinct from the LANs detected in QSO with z>3 as there is usually no QSO responsible for photoionization.
• Often structures exceed 300 p kpc and associated filaments extend beyond the field of view. Structures appear complex and extended mosaics needed
• The halo masses and redshifts are consistent with predictions of cosmological cold flows (Dekel+2009)
• Publications soon

• This project exists in part because of the superb dataset that the COSMOS collaboration has built over the years. Thank you to you all, and sorry I could not be with you in NY. And thank you Nick Scoville and all, for your vision in envisioning COSMOS... it’s just the beginning.
• Thanks also to Chris Martin and the KCWI instrument team, and Keck Observatory