Enabling the next generation of cm-wavelength studies of high-redshift molecular gas with the SKA

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Advancing astrophysics with the Square Kilometre Array
Giardini Naxos, June 13, 2014
The cosmic evolution of cool gas in galaxies

- VLA, ALMA and NOEMA: molecular gas mass estimates from CO (or dust mass)
- ALMA and NOEMA: Far-infrared lines ([CII], [NII] ..) → redshifts and ISM kinematics
- MEERKat, ASKAP, FAST, SKA: evolution of atomic HI

\[ M_{H_2} = \alpha_{CO} L'_{CO(J=1-0)} \]

(redshift Talk by Claudia Lagos)

``Blind'' detection of CO J=1-0 at \( z=2.48\)

Lentati, JW, CC et al. 2014
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Molecular emission line probes of gas at high-redshift: gas excitation

- below 50 GHz: low-J transitions (anchor) of molecular gas tracers: CO, HCN, HCO⁺, CS
- Highly excited molecular gas in quasars, starbursts (luminous and metal-rich)
Molecular emission line probes of gas at high-redshift: CMB effects

- \( z > 6 \) Ly\( \alpha \) emitters: SFRs \( \sim (5 - 20) \) M\( \odot \)/yr
- \( \text{L}^{\prime} \text{CO} < 6.1 \times 10^9 \) K km/s pc\(^2\)

Da Cunha et al. 2013

GBT CO \( J=1-0 \)

Himiko \( z=6.56 \) (lensed 4.5x)          IOK-1   \( z=6.96 \)

Wagg et al. 2009, 2012
Molecular emission line probes of gas at high-redshift: CMB effects

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- $L'_{\text{CO}} < 6.1 \times 10^9 \ K \ km/s \ pc^2$

- SKA1 CO studies limited by CMB (and metallicity dependance of $\alpha_{\text{CO}}$; e.g. Genzel et al. 2012)

Wagg et al. 2009, 2012
Da Cunha et al. 2013

GBT CO $J=1-0$

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SKA1 Band 5
Dense and star-forming molecular gas

- HCN, HCO$^+$ and CS trace dense gas ($>10^4 \text{ cm}^{-3}$)

$$M_{\text{dense}} \sim 7 L'_{\text{HCN}(J=1-0)}$$

- $L_{\text{IR}}$ and $L'_{\text{HCN}}$ correlated over $\sim$8 orders in magnitude (from Galactic cores to ULIRGs) -> star-formation (Gao & Solomon 2004; Wu et al. 2005; Carilli et al. 2005)

Galactic cores (Wu et al. 2005)

HCO$^+$ $J=1-0$ in ``the Cloverleaf'' (Riechers et al. 2006)
Predictions for surveys of molecular line emitters with SKA1

- semi-empirical predictions based on observed *Hubble* UDF galaxies (Da Cunha et al. 2013)
- SKA1-MID Band 5: 4.6 to 13.8 GHz (FoV ~ 20 arcmin² at 13.8 GHz)
- HCN in rare and luminous metal-rich quasars/SMGs (>100h with SKA1)

**Graph**

- **CS J=1-0 (z > 2.55)**
- **FWHM = 300 km/s**

**Equations**

- **observed SFR → L_{IR} [L_\odot]**
- **L_{IR} → L'_{CS} [K km/s pc^2]**
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N(galaxies) / arcmin²

4.6 – 13.8 GHz

FWHM = 300 km/s

CS J=1-0 (z > 2.55)

SKA1 - 50% (5000h)

observed SFR \(\rightarrow\) \(L_{\text{IR}}\) \([L_\odot]\)

\(L_{\text{IR}}\) \(\rightarrow\) \(L'_{\text{CS}}\) \([\text{K km/s pc}^2]\)
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*Observed data:*

- $S_{\text{line}}$ / mJy vs. log $S_{\text{line}}$
- FWHM = 300 km/s
- SKA2 (1000h)

- $CS$ $J=1-0$ ($z > 2.55$)

- $L_{\text{IR}} \rightarrow L_{\odot}$

- $L_{\text{IR}} \rightarrow L_{\text{CS}}'$ [K km/s pc²]
Predictions for surveys of molecular line emitters with SKA2

- SKA2-MID Band 5: 4.6 to 24 GHz (FoV ~ 11 arcmin² at 24 GHz)
- Cold molecular gas history of the Universe at 4 < z < 5 (epoch of massive galaxy formation) could be measured through CO line emission with SKA2

Observed SFR $\rightarrow L_{IR}$ [$L_\odot$]

$L_{IR} \rightarrow L'_{CS}, L'_{HCN}, L'_{CO}$ [K km/s pc²]
Summary

1) dense gas tracers (HCN, HCO, CS) directly probe star-forming gas, but current facilities lack sensitivity to detect low-\(J\) lines at high-redshift

2) SKA1 band 5: detections of low-\(J\) emission from dense gas tracers (CO with ALMA), however surveys (and imaging) would be better suited for SKA2

3) cold molecular gas history of the Universe at \(4 < z < 5\) during the epoch of massive galaxy formation could be measured through CO line emission with SKA2
Great observatories for the coming decades

E-ELT optical/IR  
Programme approved

ALMA: mm/submm  
Chajnantor Plateau @ 17,000 ft  
Early science now  
Inaugurated on 13th March 2013

TMT

James Webb Space Telescope  
due for launch in 2018

EUCLID:  
~€1B, launch 2020

SKA phase 1 and 2

LMT

CCAT
Exploring the Universe with the world’s largest radio telescope

Phase I: 2020
- 250,000 element Low Frequency Aperture Array
- 96 survey enabled dishes
- 254 dishes

Phase II: 2024
- >250,000 element Low Frequency Aperture Array
- Mid Frequency Aperture Array
- 2500 dishes

Science
- Cosmic Dawn & Reionization
- Cosmology & Galaxy Evolution
- Pulsars
- Cosmic Magnetism
- Cradle of Life

Frequency Bands:
- 50 MHz
- 100 MHz
- 1 GHz
- 10 GHz