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

Jeff Wagg
SKAO
UK

Elisabete Da Cunha, Chris Carilli, Fabian Walter, Manuel Aravena, Ian Heywood, Eric Murphy, Dominik Riechers, and Ran Wang

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

\[ M_{H_2} = \alpha_{CO} L'_{CO(J=1-0)} \]
(review by Bolatto et al. 2013)

``Blind'' detection of CO J=1-0 at \( z=2.48 \)
COSMOS
Lentati, JW, CC et al. 2014
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**VLA Ka-band (38 – 38 GHz) deep field toward COSMOS and GOODS-North (PI: Riechers)**

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

GBT CO $J=1-0$

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


Da Cunha et al 2013
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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)
Dense and star-forming molecular gas

- HCN, HCO$^+$ and CS trace dense gas ($>10^4$ 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)

observed SFR $\Rightarrow$ $L_{IR}$ [$L_\odot$]

$L_{IR} \Rightarrow L'_{CS}$ [K km/s pc²]
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**Graph:**

- SKA1 - 50% (5000h) CS J=1-0 (z > 2.55)
- FWHM = 300km/s

**Equations:**

- observed SFR $\rightarrow L_{IR} [L_\odot]$
- $L_{IR} \rightarrow L_{CS}' [K \text{ km/s pc}^2]$
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\[ C_{\text{S}} J=1-0 \quad (z > 2.55) \]

\[ \text{FWHM} = 300\text{km/s} \]

\[ \text{observed SFR} \quad \Rightarrow \quad L_{\text{IR}} \quad [L_\odot] \]

\[ L_{\text{IR}} \quad \Rightarrow \quad L'_{\text{CS}} \quad [\text{K km/s pc}^2] \]
Predictions for surveys of molecular line emitters with SKA2

observed SFR  $\Rightarrow$ $L_{\text{IR}}$ [L$_{\odot}$]

$L_{\text{IR}}$ $\Rightarrow$ $L'_{\text{CS}}$, $L'_{\text{HCN}}$, $L'_{\text{CO}}$ [K km/s pc$^2$]

- SKA2-MID Band 5: 4.6 to 24 GHz (FoV $\sim$ 11 arcmin$^2$ 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
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

$L_{IR} \sim 10^{12} \, L_\odot$
$M_{dyn} \sim 5 \times 10^{11} \, M_\odot$
$M_{H_2} \sim 10^{11} \, M_\odot$
$t_{univ} \sim 2.2 \, \text{Gyr}$

similar sensitivity to HCN $J=1-0$ at $z \sim 4$ with SKA2 in 1000h
Great observatories for the coming decades

- **E-ELT optical/IR**
  - Programme approved

- **TMT**

- **James Webb Space Telescope**
  - Due for launch in 2018

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

- **EUCLID**
  - €1B, launch 2020

- **SKA phase 1 and 2**

- **CCAT**

- **LMT**
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