Synergy with Line Intensity Mapping

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on behalf of

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and the SKA CD/EOR Science Working Group
Current 21cm Intensity Mapping Efforts

Intensity mapping: low-resolution, not resolving individual sources, CMB-like, in 3D

- 0.5<z<2.5, HI traces underlying matter distribution, can be used to measure Baryon Acoustic Oscillations (BAO), 109 h⁻¹ Mpc scale => dark energy

- 6<z<10, Epoch of Reionization (EoR), HI shows tomographic history of reionization, ~20-50 Mpc scale => astrophysics
Other line intensity mapping

- **CO IM** - CO rotational lines (CO(1-0) at 115 GHz rest frame): Carilli 2011, Gong+11, Lidz+11, Pullen+13
- **[CII] IM** - singly ionized carbon (158 μm rest frame): Gong+12
- **Lyman-alpha IM** - Lya emission (0.1216 μm rest frame): Silva+12, Pullen+13

![Graph showing various emission lines and their rest wavelengths](chart.png)

Visbal, Trac, Loeb 2011
Line Intensity Mapping

derived from Tegmark & Zaldarriaga 08
**Epoch of Reionization**

- A complementary view of Cosmic Reionization:
  - 21cm IM traces neutral IGM
  - CO/C+/Lyα IM traces ionized bubbles caused by star formation activities, study clustering properties.
  - ALMA/JWST offers exquisite view of ionizing sources

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Jonathan Pritchard
ITAMP 2011
Intensity mapping measures the integrated CO/[CI]/Lyα luminosity function, down to faint objects. Can be related to SFR(z).
CO intensity mapping survey

- Expected T~1 μK (Gong+ 10, Carilli 11, Lidz+ 11; also Obreschkow et al. 2009).
- HI-CO anti-correlates on large-scales, constraining size evolution of ionized regions at EoR
- May be detectable. Small aperture interferometer (DACOTA, G. Bower, D. Marrone, D. Deboer, T.-C. Chang) or focal-plane arrays (T. Readhead, S. Church, J. Sievers, C. Chiang).

Lidz et al. 2011
SKA1-low 21cm x SKA1-mid CO?

- Assume fiducial 21cm EoR survey
- Assume SKA1-mid highest-frequency band, z=8 CO(1-0) can be observed at 13GHz, 500 hours
- SKA1-mid IM in single dish mode helps, but not enough. Will need other CO programs.

Yan Gong
A 200-300 GHz bolometer array with a spectrometer can observe redshifted [CII] at $6 < z < 9$. 

Gong et al. 2012
A [CII] Intensity Mapper for EoR at 6<z<9

- 1840 TES bolometer array
- 195-295 GHz, 32 channel spectrometer
- R=200
- mounted on JCMT/GLT
- currently under construction
- PI: Jamie Bock (Caltech), Co-I: Matt Bradford (JPL), T.-C. Chang (ASIAA), Asantha Cooray (UCI)
- C+ IM traces star formation activities
- 240 hours of observation, starting ~2016

**Time-Pilot collaboration**
21cm x Lya

21cm x Lya cross power spectrum

Silva et al. 2013

Lya power spectrum at z=7

Pullen et al. 2013
SPHERX Lya Intensity Mapper

- A high-throughput, low-resolution infrared spectrometer satellite
- PI: Jamie Bock, Olivier Dore et al. (JPL/Caltech)
- Currently under review

### Technical Specifications

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical-IR imaging spectrometer</td>
<td></td>
</tr>
<tr>
<td>$\lambda = 0.9-5 , \mu m$</td>
<td></td>
</tr>
<tr>
<td>$\lambda/\Delta \lambda = 40$ and $150$</td>
<td></td>
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<tr>
<td>20cm telescope</td>
<td></td>
</tr>
<tr>
<td>Passively cooled</td>
<td></td>
</tr>
<tr>
<td>6” pixel</td>
<td></td>
</tr>
<tr>
<td>3.5x7 deg.$^2$ FOV</td>
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</tbody>
</table>
Summary

• Line intensity mapping is a new and interesting path to improve our understanding of EoR (and probe the large-scale structure).

• Theoretical modelling of the line strength is still uncertain.

• Existing facility explorations:
  
  
  
  • Carma/SZA: CO power spectrum limits at z=2-3 (Keating et al. in prep)
  
  • Pilot programs are on-going/planned: Time-pilot ([CII]), SPHERX (Lya), Dacota/AMiBA-upgrade (CO). Stay tuned!
Backup slides
21 cm x CII

Can be powerful in revealing:
- SFR(z)
- X_HI(z)
- Bubble Size (z)

Gong+12
TIME-pilot: Tomographic Ionized-C Mapping Experiment

Figure 1: EoR luminosity density and photon production. The lower points with error bars show existing measurements with ground and HST Lyman-dropout surveys, in particular the recent HST/CANDELS measurements. These estimates only include the bright galaxies and provide a lower bound. By extrapolating the faint-end slope of the UV luminosity function of detected galaxies, one can obtain an estimate of the total photon density, shown by black triangles. The three lines labeled with different values of the ratio $C/f_{esc}$, the gas clumping to escape-fraction ratio, show the requirement on the UV luminosity density for reionization. Simulations generally prefer the range of $C/f_{esc} = 10$ to $30$. The blue shaded region shows the neutral epoch of the universe, consistent with existing bounds on the CMB optical depth from WMAP. The red region shows the redshift and UV luminosity density region where TIME-Pilot with the default survey (Table 2) is predicted to make an $S/N \simeq 7$ measurement of the [CII] intensity power spectrum.

Adopted from Finkelstien+12
• At 200-300 GHz, contributions from high-z [CII] and lower-z CO emissions.
• [CII] and CO model uncertainties are still large.
• Their correlation with SFR is not solidly understood.
• Lower-z CO needs to be “masked”.
• Will learn more from ALMA, JVLA, PdBI observations (e.g. Walter et al. 2013).
**TIME-pilot:**
Tomographic Ionized-C Mapping Experiment

- First detection of [CII] clustering signals.
- Measure the integrated [CII] emissions, including contributions from small, otherwise undetectable sources.
- Reveals SFR at high-z.
- In case of no detection, upper limits are interesting, too.
What can we learn so far?

Secure your Universe: Cross-correlations as a Cosmological Carbon Monoxide Detector

Pullen, Chang, Dore, Lidz 2013

(121°–126°, 0°–4°), (119°–128°, 4°–6°), (111°–119°, 6°–25°), (111.5°–117.5°, 25°–30°), (110°–116°, 32°–35°), (246°–251°, 8.5°–13.5°), (255°–270°, 20°–40°), (268°–271°, 46°–49°), and (232°–240°, 26°–30°). Finally, we cut pixels that appeared to have severe photometric calibration errors (≳5 mag).

After the cuts, the survey region comprises 534,564 N_res = 9 pixels covering 7010 deg².

2.2.2. SDSS LRGs

We use the LRG catalog composed by Kazin et al. (2010) [14]. LRGs are the most luminous galaxies in the universe, making them important for probing large volumes. They are also old stellar systems with uniform spectral energy distributions and a strong discontinuity at 4000 Å, which enable precise photometric redshifts. The LRG catalog consists of 105,623 spectroscopic LRGs from redshifts 0.16 < z < 0.47. We do not make any alterations to this catalog. We survey region comprises approximately 638,583 N_res = 9 pixels covering 8374 deg².

2.3. WMAP-QSO Cross-Data Set

We intersect the pixel sets from the temperature and quasar map to produce two sets of maps that can be cross-correlated. This operation leaves each map with 441,228 N_res = 9 pixels covering 5786 deg² with ∼7 arcmin pixel resolution. Since each WMAP band probes a separate redshift range for each of the CO emission lines, we also divide the quasar map into 8 maps, two for each of the WMAP bands. Note that some of the bands for CO(1-0) will intersect in redshift with other bands for CO(2-1).

We list the properties of the 4 WMAP maps and 8 quasar maps in Table 1 as well as the probed spatial scale determined by our pixel size. Note that the Ka(2-1) redshift range exceeds the redshifts of the quasars; therefore, we will not determine any limits on the CO(2-1) line with the Ka band.

2.4. WMAP-LRG Cross-Data Set

We also intersect the areas of the temperature and LRG maps for cross-correlation, with 619,708 N_res = 9 pixels covering 8126 deg². Note that the WMAP W band is the only band that overlaps with the LRG sample, and this is true only for the CO(1-0) line. Thus, we will only get one constraint from this cross-correlation. However, the number of LRGs in this redshift range is much more than the number of quasars, so we expect a more significant constraint than that from the quasars.

Table 1. WMAP redshift bins for CO emission lines J=1→0 and J=2→1 with the quasar (QSO) counts from the QSO map (T x QSO intersected map).

For reference, we write in parenthesis the transverse scale corresponding to the pixel scale in Mpc/h for each z band probed. As stated above, the total number of QSOs in DR6 is 1,172,157.

<table>
<thead>
<tr>
<th>Band</th>
<th>z(1 → 0) ([Mpc/h])</th>
<th>N_QSO(1 → 0)</th>
<th>z(2 → 1) ([Mpc/h])</th>
<th>N_QSO(2 → 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ka</td>
<td>2.151–2.898 (9)</td>
<td>90,780 (74,395)</td>
<td>5.302–6.796 (13)</td>
<td>80 (63)</td>
</tr>
<tr>
<td>Q</td>
<td>1.547–2.121 (7)</td>
<td>146,111 (121,297)</td>
<td>4.094–5.242 (11)</td>
<td>573 (466)</td>
</tr>
<tr>
<td>V</td>
<td>0.691–1.130 (5)</td>
<td>62,172 (51,818)</td>
<td>2.382–3.260 (9)</td>
<td>27,032 (22,180)</td>
</tr>
<tr>
<td>W</td>
<td>0.103–0.373 (1)</td>
<td>42,184 (34,400)</td>
<td>1.206–1.746 (6)</td>
<td>140,819 (116,791)</td>
</tr>
</tbody>
</table>

(out of 1,172,157 QSOs in BOSS DX6)
Figure 7. Limits on $T_{CO}$ of CO(1-0) and CO(2-1) over four redshift bins. The dashed line is the fiducial temperature from Model A for $M_{co, min} = 10^9 h^{-1} M_\odot$ and the dotted line is the fiducial temperature from Model B for $SFR_{min} = 0.01 M_\odot/yr$.

- No cross-correlation detection!
- Set upper limits on $T_{CO}[1-0](z)$ and $T_{CO}[2-1](z)$
- Need to be careful about potential contaminations, including SZ, spinning dust, etc.
- We remove CMB contribution by subtracting other WMAP bands
- SPTpol x BOSS expects SN>15 detections with (90, 150, 220) GHz (CO J=3,5,8).
# Time-Pilot specs

<table>
<thead>
<tr>
<th>Table 1: TIME-Pilot Experiment Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Final $f/#$</td>
</tr>
<tr>
<td>Cryostat</td>
</tr>
<tr>
<td>Number of spectrometers</td>
</tr>
<tr>
<td>Estimated end-to-end optical efficiency</td>
</tr>
<tr>
<td>Total # of detectors</td>
</tr>
<tr>
<td>Instantaneous FOV</td>
</tr>
<tr>
<td>NEI on sky [(MJy/sr)$^{\sqrt{sec}}$]</td>
</tr>
</tbody>
</table>

### Instrument System Parameters

<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>LF Band</strong></th>
<th><strong>HF Band</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range [GHz] (redshift)</td>
<td>194–231 ($z=5.8–7.3$)</td>
<td>231–294 ($z=7.3–8.8$)</td>
</tr>
<tr>
<td>Grating resolving power $R = \nu/\delta \nu$</td>
<td>200–250</td>
<td>170–200</td>
</tr>
<tr>
<td># of Bolometers per sub-band (42 per full spectrometer)</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>$\nu/\delta \nu$ per bolometer</td>
<td>93–116</td>
<td>89–112</td>
</tr>
</tbody>
</table>

### Waveguide Grating Design

<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>LF Band</strong></th>
<th><strong>HF Band</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting transition temperature $T_C$</td>
<td>450 mK (Ti) + 1.2 K for lab testing (Al)</td>
<td>250 mK via $^3$He cooler</td>
</tr>
<tr>
<td>Base temperature</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>TES safety factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductance G [pW/K] at $T_C$</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Detector + MUX NEP [$10^{-18}$ W Hz$^{-1/2}$]</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Photon NEP [$10^{-18}$ W Hz$^{-1/2}$]</td>
<td>15–17</td>
<td>17–24</td>
</tr>
<tr>
<td>Absorber size [mm]</td>
<td>3.0 $\times$ 2.5</td>
<td>3.0 $\times$ 3.3</td>
</tr>
<tr>
<td>Silicon nitride leg geometry (0.25-$\mu$m thick nitride)</td>
<td>183$\mu$m $\times$ 3$\mu$m</td>
<td>138$\mu$m $\times$ 3$\mu$m</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>2.4 pJ/K</td>
<td>2.9 pJ/K</td>
</tr>
<tr>
<td>Time constant (including TES electrothermal feedback)</td>
<td>14 ms</td>
<td>16 ms</td>
</tr>
</tbody>
</table>

### TES Bolometer Parameters

<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>LF Band</strong></th>
<th><strong>HF Band</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Target field size</td>
<td>78 arcmin $\times$ 0.5 arcmin rectangle</td>
<td></td>
</tr>
<tr>
<td>Total integration time</td>
<td></td>
<td>240 hours</td>
</tr>
<tr>
<td>Intensity RMS, per beam, per spectral bin</td>
<td></td>
<td>140$\mu$Jy</td>
</tr>
</tbody>
</table>