Cosmology with Line Intensity Mapping

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Line Intensity Mapping

Cosmic Dawn

EoR: Epoch of Reionization

LSS: Large-Scale Structure

SDSS III

CMB

$21\text{cm}$

Spectral line

- Up to $10^{16}$ modes to $z \sim 50$ (Hubble/Jeans)$^3$

derived from Tegmark & Zaldarriaga 08
"Intensity Mapping" (Chang+ 2008, Wyithe & Loeb 2008):

- Measure the collective emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.
- Use spectral lines as tracers of structure, retain high frequency resolution thus redshift information.
- Measure brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D.
- Low-angular resolution redshift surveys: economical, large survey volumes.
- Confusion-limited. Foreground-limited.
21cm Intensity Mapping Experiments

• Significant national interest in BAO searches.
• Putting together team to propose/build southern hemisphere experiment.
• Lots of synergy w/ SKA - several MeerKAT key projects would be significantly improved for few % of MeerKAT cost. e.g. pulsar search, H-I absorber search, radio transient search.
• SKA very interested in prospect of correlator capable of handling SKA phase 1 already working and on-site.
• Hydrogen Intensity and Real-time Analysis eXperiment.

Above: rock Hyraxes.
Status Update:
21cm Intensity Maps at z~0.8
with Green Bank Telescope
GBT-HIM

Pilot program at the Green Bank Telescope (GBT)

- Frequency: 700-900 MHz
  - $0.6 < z < 1$

- Spatial beam ~ 15’
  - $9 \, h^{-1} \, Mpc$ at $z \sim 0.8$

- Spectral channel ~ 24 kHz
  - binned to 0.5 MHz
  - $\sim 2 \, h^{-1} \, Mpc$

- 100-m diameter. Large collecting areas

- Foregrounds are $\sim 1000\times$ stronger than the 21cm signals

- First detection in cross-correlation with DEEP2 galaxies at $z=0.8$
  (Chang, Pen, Bandura, Peterson, 2010, Nature)
21 cm Intensity Mapping at the GBT

- Frequency: 700-900 MHz
  - $0.6 < z < 1$
- Spatial beam $\sim 15'$
  - $9 \, h^{-1} \, \text{Mpc}$ at $z \sim 0.8$
- Spectral channel $\sim 24 \, \text{kHz}$
  - binned to 0.5 MHz
  - $\sim 2 \, h^{-1} \, \text{Mpc}$

- 200-hr HI survey of the WiggleZ fields at $0.6 < z < 1$
- HI cross-power and auto-limits in 2013 at $z=0.8$ implies:
  - $\Omega_{\text{HI}} b_{\text{HI}} = [0.62^{+0.23}_{-0.15}] \times 10^{-3}$

**Auto-power limits, Switzer+13, GBT-HIM**

**Cross-power, Masui+ 13, GBT-HIM**
GBT-HIM Status Update

- Analysis of ~800 hours of GBT observations 2010-2015.
  - WiggleZ 1hr, 11hr, 15hr, 22hr fields
- Improve HI power spectrum limits
- Measure HI-optical cross-power RSD effects
- Focus on the 1hr field, ~100 square deg, 0.6 < z < 1:
  - Alternative Foreground cleaning techniques (Wolz + GBT-HIM team, 2016)
  - Polarization calibration improvement (Liao, Chang et al. 2016)
  - Polarization leakage power spectrum estimates (To, Chang et al., in prep)
  - Handling of residual ground-spill contamination (Liao, Chang, Masui et al., in prep)
Forefront Mitigation: SVD v.s. ICA

Laura Wolz et al., +GBT-HIM team, 2017

- Foreground Projection/Subtraction Methods:
  - SVD - singular value decomposition: spectral and spatial eigenmodes (Switzer, Chang, Masui, Pen, Voytek 2015).
  - SVD: signal loss, compensated by calculating transfer functions.
  - ICA: no signal loss. But more difficulty in handling systematics.
  - ICA x ICA, SVD x ICA maps: no obvious improvement on the power spectrum limits.
Precision polarization calibration at GBT

- GBT Mueller 4 x 4 beam

\[ S' = J_B R_{\phi} (\phi) S \]

- Make use of quasars, pulsars and noise-diode (switching at 16 Hz) to constrain six-parameter Jones/Mueller matrix.
- Reached \( \sim 0.6\% \) precision on-axis (boresight).
- Correct for ionospheric RM \( \sim 2 \) deg m\(^2\). Polarization angle rotation \( \sim 10-20 \) deg.
Leakage power spectrum estimate

- Upper limits on leakage power spectrum contamination
  - Estimate (scan-averaged) pol-beam deconvolved maps, and calculate expected leakage.
  - Polarization leakage power spectra < 10% HI upper limits but can be 10x expected HI signals; working on detailed simulations and error estimates
  - Incorporate full polarized beam model in map-making?

To, Chang, Liao, GBT-HIM, in prep.
Work in progress:
Updated HI auto-power spectrum at $z \sim 0.8$

- A $\sim$4-sigma detection… of systematics?
- Currently running jackknife tests.
- More SNR would help!

Chang, Liao, To + GBT-HIM, in prep.
Cross-correlation:
21 cm Intensity Maps at z~0.08
with Parkes Telescope
Parkes HI-2dF Cross-power spectrum

- Parkes L-band multi-beam observation, 0.06 < z < 0.1, over 1500 sq. deg., 150 hrs
- Significant cross-power spectrum with 2dF galaxy measured at ~12 sigma.
- Comparison with individual detection HI surveys, HIPASS and ALFALFA.
  - Cross-power amplitude \( \sim T_b b_{\text{HI}} b_{\text{opt}} r \)
  - \( b_{\text{HI}}=0.85, T_b=0.064 \text{ mK} \) (ALFALFA; Marin+ 2010), \( b_{\text{opt}}\sim 1 \) (Cole+ 2005).
  - Cross-power shape: curves include linear + non-linear RSD effects.
  - \( r \) likely < 1. Power deficit at \( k\sim1.5 \text{ h/Mpc} \)
• Cross-correlating with 2dF blue and red galaxies separately.
• HI follows distribution of blue galaxies but does not trace red galaxies at $k \sim 1.5 \, h/\text{Mpc}$
• HI-galaxy cross-correlation coefficient appears scale- and color-dependent.
• Neither simple HI halo model (e.g. Padmanabhan+16) nor naive large-scale sims can capture this feature. We need better small-scale modeling!
EoR Sciences

[CII] Intensity Maps at z~5-9 with TIME
And all other spectral lines

- CO IM - CO rotational lines (CO(1-0) at 115 GHz rest frame): Righi+ 08, Visbal & Loeb 2010, Carilli 2011, Gong+11, Lidz+11, Pullen+13, Breysse+14, Breysse+15, Li+15, Mashian+15, Keating+15, Keating+16
- [CII] IM - singly ionized carbon (158 μm rest frame): Gong+12, Silva+14, Yue+15, Serra+16, Cheng+16
- Lyman-alpha IM - Lya emission (1216 Å rest frame): Silva+12, Pullen+13, Croft+16
- H-alpha IM - Ha emission (6562 Å rest frame): Gong+16; Silva+17
- HeII IM - HeII (1640 Å): Visbal, Haimann, Byran 2015
CO/\[\text{CII}\]/Ha trace star formation activities on large-scales at EoR, anti-correlate with 21cm emissions on ionized bubble scales and can be used to derive bubble evolution and reionization history (Lidz et al. 2009; Chang et al. 2015).

- Continuum foregrounds are much less of an issue. Need to worry about line interlopers.
TIME: [CII] Intensity Mapper
Tomographic Ionized-C Mapping Experiment

- A [CII] Intensity Mapper for EoR at 6<z<9
- 1840 TES bolometer array
- 195-295 GHz, 32-channel spectrometer
to be installed on APA 12-m.
- Caltech (J. Bock), JPL (M. Bradford, T.-C. Chang), ASIAA (C.-T. Li), UCI (A. Cooray), U Arizona (D. Marrone)
- Engineering run expected fall 2018.
- [CII] IM traces star formation activities
- 1000 hours of observation, starting ~2019
- Measure [CII] P(k) at several 10s of sigma (model dependent)
TIME measures CO/H$_2$ abundance at $z=0.5$-2

- TIME will measure multiple CO J rotational transitions at $0.5 < z < 2$
- Can be achieved via in-band cross-correlations of different J lines
- TIME will constrain the cosmic molecular hydrogen abundance across redshifts

TIME collaboration
CO, [CII] signal de-confusion

- High-z [CII] and low-z CO rotational lines can be confused in TIME.
- Can use the redshift-dependence of CO and [CII] from observing to comoving coordinates to distinguish the lines (Lidz & Taylor 2016; Cheng, Chang et al. 2016).

TIME collaboration (Cheng, Chang et al. 2016)
EoR Sciences
Lya, Ha Intensity Maps at z~6-9
with SPHEREx
Line Intensity Mapping with SPHEREx

SPHEREx: low-resolution spectroscopic all-sky survey

For every ~3" pixel over the entire sky:

- R=40 spectra spanning (0.75 μm < λ < 4.81 μm).
- R=150 spectra (4.1 μm < λ < 4.81 μm).

- SPHEREx will measure 3D clustering of multiple line tracers at high SNR their luminosity-weighted biases.
- SPHEREx will map SFR throughout cosmic time
- SPHEREx might have sensitivity to detect Lyα from EoR
- SPHEREx currently in MIDEX competition.

Doré, Bock et al., arXiv:1412.4872
Summary

- Line Intensity Mapping offers an exciting and unique probe of a significant fraction of the Universe

- 21cm Intensity Mapping proof of concept demonstrated at $z \approx 0.8$ (Chang et al. 2010).
  - Opens up 21-cm 3D large-scale structure studies (GBT-HIM multi-beam array; HIRAX, CHIME, Tian-Lai in progress; and possibly SKA1-mid.)

- [CII] Intensity Mapping offers a complementary probe of the Epoch of Reionization

- CO Intensity Mapping: a $\sim$2-sigma detection at $z=2-3$ (Keating et al. 2016).
  - COMAP (PI: K. Cleary; Caltech) and AIM-CO (PI: Y.-H. Chu, ASIAA) underway

- Lyman-alpha IM: a 3-sigma cross-correlation detection at $z \approx 2-3.5$ (Croft et al. 2016).
  - SPHEREx may potentially probe Lya IM at $z \sim 6-8$. HETDEX at $z=2-3$.

- EoR 21-cm detection may come from several groups with different approaches soon (LOFAR, PAPER, MWA). HERA/SKA1-LOW will bring next generation transformational sciences.