Status of CHIME: The Canadian Hydrogen Intensity Mapping Experiment

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Photo Credit: Sasse
Outline

• Description of science goal
  - *Measurement of the Baryon Acoustic Oscillations in the distribution of neutral hydrogen between redshifts 0.8 and 2.5.*

• Virtual tour of CHIME

• Current status and first look at data

• Challenges
  - *Foreground removal*
  
  - *Instrument characterization*
    - Complex gain calibration
    - Beam calibration
  
  - *RFI Excision / Mitigation*

• Forecast on cosmological constraints
Baryon Acoustic Oscillations

Initial density perturbations result in sound waves that propagate in the photon-baryon fluid of the early universe. These are “frozen in” at recombination, leaving acoustic peaks in the CMB and matter power spectrum.

**Evolution of a primordial density perturbation**

Baryon Acoustic Oscillations

Movies by Adam Hincks: http://adh-sj.info/bao_cmb.php
BAO as Cosmological Ruler

\[ r_s = 150 \text{ Mpc (± 0.3%)} \]

Planck Collaboration 2013

Image by Gen Chiaki and Atsushih Taruya
Spectroscopic Galaxy Surveys

Fig. 2.—As Figure 2, but plotting the correlation function times the square of the number density variance. This shows the variation of the peak at 20 degrees. The selection of LRGs is highly sensitive to errors in the large-scale redshift-space correlation function. This of course corresponds to complete suppression of purely radial modes. The magenta suppression is negligible, only 5%. It is interesting to note that although the data at the best-fit parameters at all scales makes the plot look cosmetically perfect, but considering the uncertainty in the number density out to 200 h\(^{-1}\) Mpc, the large-scale redshift-space correlation function of the SDSS LRG sample is reduced by 13% (86%). The error bars are from the diagonal element of the selection function, in which the redshifts of the random and control samples are simply picked randomly from the observed redshift distribution when we move the selection boundaries to restrict the sample. Such photo-boosting the large-scale correlations too much causes an increase in the angular diameter distance from the correlation function. However, the situation is more favorable on large scales that is 20% on smaller scales. The pure CDM model (magenta) is actually consistent with the SDSS catalog, although this would translate to about 0.02 in the Einstein-de Sitter model, and 0.01 in the open model. Varying the stellar locus find only 1% scatter in the baryon acoustic oscillation scale.

Notes:
- Assessments of calibration errors based on the color of the stellar locus find only 1% scatter in the sky distribution of LRGs.
- The selection of LRGs is highly sensitive to errors in the large scale correlation function and errors in the flat field vectors early in the survey (Stoughton et al. 2002). Such errors will average down on larger scales even more quickly. The coherence scale of the calibration errors are 20 independent calibrations being applied to a given observation night, about 0.02 in the redshift, and the coherence scale of the calibration errors would cause anomalies in the correlation function. However, the situation is more favorable on large scales that is 20% on smaller scales. The pure CDM model (magenta) is actually consistent with the SDSS catalog, although this would translate to about 0.02 in the Einstein-de Sitter model.
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SDSS
Eisenstein et al. 2005

SDSS
Blanton et al. 2003

BAO Scale

Z
0 0.05 0.1 0.15 0.2 0.25

ξ ∝ h^2

Ω_m h^2 = 0.14 (bottom with peak, blue), all with the peak on axis. The models are related. Note that the vertical axis mixes logarithmic and linear scales. The error bars are from the diagonal element of the selection function, in which the redshifts of the random and control samples are simply picked randomly from the observed redshift distribution when we move the selection boundaries to restrict the sample. Such photo-boosting the large-scale correlations too much causes an increase in the angular diameter distance from the correlation function. However, the situation is more favorable on large scales that is 20% on smaller scales. The pure CDM model (magenta) is actually consistent with the SDSS catalog, although this would translate to about 0.02 in the Einstein-de Sitter model, and 0.01 in the open model. Varying the stellar locus find only 1% scatter in the sky distribution of LRGs.

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BAO in the Galaxy Correlation Function

The inset shows an expanded view with a linear vertical scale. The error bars are from the diagonal element of the covariance matrix.

The relationship between bias and redshift (Zehavi et al. 2005) is scale-dependent. Varying the redshift by 1% alters the amount of large-to-small scale correlation, but changing the lognormal realizations by only 1.3 changes the best-fit due to the data points on intermediate scales.

We also include an integral constraint correction in the form of light blue dashed lines.

The correlation function because the pair separations of interest are usually close to the best-fit due to the data points on intermediate scales. Subtracting 0.002 from the multipoles and adding 0.3 modifies the amplitude of the power spectrum.

The explanation for this is given in Appendix A.
Hydrogen Intensity Mapping

- Spectroscopic galaxy surveys expensive, difficult at high-z

- Interested in much larger scales, do not need to resolve individual galaxies

- Instead, measure the aggregate 21 cm emission from neutral hydrogen
  - Observing frequency maps to redshift slice
  - Probe “redshift desert” (1.4 < z < 2.5)

<table>
<thead>
<tr>
<th>Observable</th>
<th>z=2.5 (400 MHz)</th>
<th>z=0.8 (800 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \theta_{\text{BAO}}(z) = r_s / D_M(z)$</td>
<td>1.35°</td>
<td>3°</td>
</tr>
<tr>
<td>$\Delta z_{\text{BAO}}(z) = r_s H(z) / c$</td>
<td>12 MHz</td>
<td>20 MHz</td>
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</tbody>
</table>

Blanton et al. 2003
Smoothed to CHIME resolution
chime

a collaboration between

THE UNIVERSITY OF BRITISH COLUMBIA

McGill

West Virginia University

Yale University

Dominion Radio Astrophysical Observatory

MIT

Massachusetts Institute of Technology
Drone Flight Over CHIME
Dominion Radio Astrophysical Observatory

CHIME

Pathfinder

18% of band lost due to RFI

Local Oscillator

LTE

TV Channels

Dominion Radio Astrophysical Observatory is located in Penticton, BC.

Seth Siegel

Inter-institutional Laboratory for e-Astronomy Webinar
Cylindrical Transit Interferometer

Movie by Peter Klagge
Cylindrical Transit Interferometer

A Computerised Telescope

In a conventional telescope, the electric field at the image plane is the Fourier transform of the field over the aperture.

\[(x', y') \quad (x, y, z)\]

- Cylinder focuses light only in EW direction
- Gives us large FOV
Cylindrical Transit Interferometer

- FFT telescope in NS direction
- 256 beams per cylinder

Slide from Liam Connor
Cylindrical Transit Interferometer

- 1024 beams from full 4-cylinder CHIME
Cylindrical Transit Interferometer

Haslam 408 MHz Map
CHIME Parameters

- 4 cylinders (each 20 m x 100 m)
  - 8,000 m² collecting area
- 1024 dual polarization feeds

<table>
<thead>
<tr>
<th>Bandpass</th>
<th>400 MHz</th>
<th>800 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>21cm redshift</td>
<td>2.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Beam Size</td>
<td>0.52° (45 Mpc)</td>
<td>0.26° (10 Mpc)</td>
</tr>
<tr>
<td>E-W FoV</td>
<td>2.5°</td>
<td>1.3°</td>
</tr>
<tr>
<td>N-S FoV</td>
<td>~100°</td>
<td></td>
</tr>
</tbody>
</table>

- Cosmology
  - Cosmic variance limited measurement of BAO between \( z = 0.8 - 2.5 \)
- Pulsars
  - Precise timing of known msec pulsars
- Fast Radio Bursts
  - Detect on order 10 FRBs per day

- 390 kHz frequency resolution
- Maps 1/2 the sky each day
- \( T_{\text{receiver}} = 50 \text{ K} \)
- 80 μJy / pixel daily sensitivity
- Collecting data since March.
UBC graduate student Meiling Deng who led design of CHIME cloverleaf antennas
Reflector

Analog Receiver Chain

FPGA Digitizer / Channelizer

GPU Correlator

Real-time Backends

Disk
Figure 8. (a) Image of the CHIME amplifier and band-defining filter. Input on the left. (b) Gain and passband of the filter-amplifier block labeled filter amp plotted along with the full analog chain labeled cascade. The passband of the filter amplifier block is designed to be very flat with frequency. The entire analog chain has a slope from low to high frequency primarily due to the LNA gain and analog cabling.

- Commodity gigabit ethernet switches are used to collect the data onto a server which stores the integrated data. A server on this same network is used to configure and monitor the hardware in the array.

Table 2 summarizes the key design parameters of the CHIME Pathfinder’s digital backend. In addition to those, the system had to be designed with enough flexibility to allow testing of real-time gain corrections, RFI removal, high-speed and triggered data tapping for ancillary science such as pulsar and radio transient signal analysis, and beamforming along each cylinder. The design is also required to be scalable to 2560 inputs for the full CHIME instrument.

The hardware, firmware and software components of the digital backend are described in more detail in the sections below.

5.1 Analog-to-digital converter daughterboards

The analog-to-digital conversion of the feed signals is performed using custom double-wide FPGA mezzanine card (FMC) compliant daughter boards equipped with two E2V EV8AQ160 analog-to-digital (ADC) chips (see Figure 10). Each ADC chip has four inputs that can sample at up to 1.25 GSps at 8 bits.

The sky signal in the absence of man-made signals is well encoded with only a few bits, with 4 bits having the effect of increasing any properly amplified white noise system temperature by \( \sim 2 \) percent. However, man-made RF power consists of both broadband bursts and strong narrowband signals which require additional dynamic range. Initial testing found that 8 bit sampling will provide the dynamic range to sample the sky adequately given the RF conditions at the site.

For CHIME, the sampling rate is set to 800 MSps, and the 400-800 MHz sky signal is directly sampled using the second Nyquist zone. The analog inputs achieve more than 15 dB return-loss from 300 MHz to 1.1 GHz. The input passband is broader, from 150 MHz to 1.1 GHz. These analog components are constrained to one section.
FPGA Digitizer and Channelizer (F-Engine)

Reflectors

Analog Receiver Chain

FPGA Digitizer / Channelizer

GPU Correlator

Real-time Backends

Disk

Motherboard
16 analog inputs

Backplane
256 analog inputs

CHIME quadrant
512 analog inputs

Bandura et al. 2016, JAI
10 Gbit/s Link over Optical Fiber (x1024)

Reflector

Analog Receiver Chain

FPGA Digitizer / Channelizer

GPU Correlator

Real-time Backends

Disk

Satellite Image of CHIME

GPU Huts

Rx Huts

Reflectors

Amps, filters, etc

FPGA Digitizer / Channelizer

GPU Correlator

Disk

Real-time Backends
GPU Correlator (X-Engine)

- Reflector
  - Analog Receiver Chain
  - FPGA Digitizer / Channelizer
  - GPU Correlator
  - Real-time Backends
  - Disk

Fig. 8.— Rendered image of a node, containing all components in the baseline proposal. Power cables are omitted for clarity, but this is otherwise representative of what we expect in the final build.

Denman et al. 2015

AMD S9300x2
• Cosmology
  - Full $N^2$ visibility matrix
  - 10 sec cadence
  - 135 TB/day
  - Real time flagging and gain calibration
  - Data compression through redundant baselines (0.5 TB/day)

• Pulsar timing
  - 10 steerable beams
  - 2.56 $\mu$s cadence

• Fast Radio Burst
  - 1024 stationary beams
  - 1 msec cadence
  - 16k frequency bins
Status

- First light ceremony on September 7, 2017
- Commissioning throughout Winter 2018
- Began collecting science data on March 27, 2018
  - Compression through truncation:
    - Saving 25% of all frequency bins
      - Frequencies with minimal RFI contamination covering 630 - 790 MHz
    - Saving 25% of all baselines
      - $|u_{ew}| \leq 22\text{m}$ and $|u_{ns}| \leq 20\text{m}$
  - Also writing $N^2$ data to disk for 4 frequency bins to aid in development of real-time flagging, calibration, and compression algorithms.
- Expect to be at full capacity by October 2018

### Efficiency During First Science Run

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Total</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Inputs</td>
<td>1900</td>
<td>2048</td>
<td>93%</td>
</tr>
<tr>
<td>Frequency Bins</td>
<td>868</td>
<td>1024</td>
<td>85%</td>
</tr>
<tr>
<td>Uptime</td>
<td>49 days</td>
<td>64 days</td>
<td>77%</td>
</tr>
</tbody>
</table>
Radio Sky as seen by CHIME

702.34 MHz, YY Pol

“Dirty ring map” generated from a single sidereal day of CHIME N² data for a single frequency bin and single polarization (0.025% of total data).
Radio Sky as seen by CHIME

“Dirty ring map” generated from a single sidereal day of CHIME N² data for a single frequency bin and single polarization (0.025% of total data).

Color scale compressed by a factor of 2.5.
Radio Sky as seen by CHIME

“Dirty ring map” generated from a single sidereal day of CHIME N^2 data for a single frequency bin and single polarization (0.025% of total data).

Color scale compressed by a factor of 10.
Foregrounds

- Foregrounds are $10^5$ times brighter than the 21 cm signal.

- Foregrounds have a smooth spectrum, whereas the 21 cm signal varies rapidly with frequency because it originates from distinct structure along the line-of-sight direction.
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- Unfortunately, frequency dependent instrumental effects convert the bright foreground signal into small-scale spectral structure.
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• Unfortunately, frequency dependent instrumental effects convert the bright foreground signal into small-scale spectral structure.

• CHIME plans to characterize the transfer function of the instrument and construct optimal Karhunen-Loève filter that rotates measured data into signal/foreground modes.
Calibration Requirements

\[ V_{ij}(t) = \langle E_i(t)E_j^*(t) \rangle = g_i(t)g_j^*(t) \int d^2\hat{n} \ A_i(\hat{n})A_j^*(\hat{n})e^{2\pi i\hat{n} \cdot u_{ij}} T(\hat{n}; t) \]

- **Complex gain calibration:** Need to know complex gain to better than 0.3% on timescales > 1 minute

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- **Beam calibration:** Need to know primary beam to better than 0.1%
Complex Gain Calibration

• Currently calibrate complex receiver gain once per sidereal day by using the full visibility matrix to solve for the response of each feed to a stable, radio-bright point source (Cygnus A, Cassiopeia A, or Taurus A).
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- Results in amplitude stability at the 1% level and phase stability at the 0.01 radian level.
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- Most of the residual variation observed in amplitude is common mode (across feeds and frequency) and highly correlated with outside temperature.
- Using a thermal model to interpolate between daily calibrator transits results in amplitude stability at the 0.5% level.
**Complex Gain Calibration**

**CHIME Analog Receiver Chain**

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  - Most of the residual variation observed in amplitude is common mode (across feeds and frequency) and highly correlated with outside temperature.
    - Using a thermal model to interpolate between daily calibrator transits results in amplitude stability at the 0.5% level.

- To ensure systematic errors due to gain fluctuations are negligible compared to statistical errors, we require stability at < 0.3% (amplitude) and < 0.003 radians (phase).
  - Investigating receiver dependent thermal models and broadband signal injection techniques to further improve calibration.
Beam Calibration

- **Point Source Holography**
  - Track radio-bright point source with John Galt 26m telescope as it drifts through the beam of the CHIME feeds
  - Correlate signal from 26m with signal from every CHIME feed
    - Extracts point source signal modulated by CHIME beam (plus any common background sky)

- **Pulsar Holography**
  - Subtract pulsar ON - pulsar OFF to remove common background sky
  - ~100 msec cadence; implement in GPU
  - Characterize polarization response

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Newburgh et al. 2014
Berger et al. 2016
3.2 Gridding and averaging

We first regrid the visibilities in hour angle, using an inverse Lanczos resampling.\(^\text{\textsuperscript{\textcopyright}}\) At this point the only input to the noise covariance other than the assumption of constant instrumental noise across frequencies and baselines is RFI flagging, which assigns infinite noise to flagged time samples. We note that the telescope is not sensitive to spatial Fourier modes larger than its width $w_{EW}$ in wavelengths $\lambda_{\text{max}} = 2\pi w_{EW}$.

\[^{\text{\textcopyright}}\] https://en.wikipedia.org/wiki/Lanczos

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Berger et al. 2016

Pathfinder holography data for a single EW Pol Feed

Simulated Beam EW Pol at 703 MHz

Courtesy of Meiling Deng

Figure 3: The amplitudes of the gridded and averaged visibilities for all sources at 681 MHz for both polarisations of a single antenna near the centre of the West cylinder, and its corresponding antenna on the East cylinder. Regions of one standard deviation are shaded. The offset of the peak of the main beam is due to a 1.9 degree rotation of the Pathfinder cylinder axis from astronomical North.
RFI Excision

- Spectral-Kurtosis based implementation of pre-correlation RFI excision using CHIME’s GPU backend.

- Increase the sensitivity of the RFI removal by combining samples from CHIME’s 2048 independent feeds.

- This extra sensitivity allows for sub-millisecond RFI discrimination to detect quick broadband RFI pulses.

- Comparison with CHIME’s pathfinder concludes the discrimination power scales with the size of the array.

  Taylor et al. 2018 (in prep)
Survey Volume

- **SDSS-II**
  - 2.2 Gpc$^3$

- **6dFGS**
  - 0.4 Gpc$^3$

- **WiggleZ**
  - 3.8 Gpc$^3$

- **BOSS**
  - LRG: 20 Gpc$^3$
  - Ly-α: 150 Gpc$^3$

- **DESI (2019 - 2024)**
  - LRG/ELG: 140 Gpc$^3$
  - Ly-α: 230 Gpc$^3$

- **CHIME (2018 - 2023)**
  - 470 Gpc$^3$

Scaled such that Area = Survey Volume

Big Bang
Recombination

Cosmic Dark Ages

Reionization

$z = 1$

$z = 0.1$

$z = 10$

$z = 100$
Cosmology Forecast

Figure courtesy of Kevin Bandura

Forecasted Sensitivity

$D_{vr_s,fid}/r_s$ (Mpc h$^{-1}$)

$D_v/r_s$/$r_s$$_{fid}$

BOSS
SDSS-II
6dFGS
WiggleZ
BOSS Ly-α

CHIME 5 year survey

$z$
Cosmology Forecast

Dark energy equation of state: \( w = p / \rho \)

- Lines: Indicate range of \((w_0, w_a)\) allowed by Planck 2013 and Union2.1 SNe data
- Error bars: Predicted 2-year CHIME sensitivity

Constraints on dark energy equation of state competitive with DOE Stage IV experiments (e.g., DESI, Euclid)

Figures courtesy of Richard Shaw
Fast Radio Bursts

- Bright bursts of radio emission
- Millisecond timescales
- Very high dispersion measure
  - Located at cosmological distances
- Only 24 have been detected so far
  - Implies there are ~3000 FRBs per sky per day
- One found to repeat, localized to a dwarf galaxy 2.5 billion light-years away (Spitler et al. 2016, Chatterjee et al. 2017, Tendulkar et al. 2017)
- What are they? Lots of theories.
- CHIME expects to detect order 10 per day

Movie by NRAO Outreach: T. Jarrett (IPAC/Caltech) and B. Saxton (NRAO/AUI/NSF)
First Detection of FRBs between 400-800 MHz by CHIME/FRB

Figure 1: Dynamic spectrum plot after de-dispersion to DM = 716.6 pc cm$^{-3}$. The time is relative to the topocentric (at 400 MHz) burst peak on 2018 July 25 at 17:59:43.115 UTC. Intensity data for the two beams in which FRB 180725A was detected are shown. These approximately 0.5° wide and circular beams were at RA, Dec = (06:13:54.7, +67:04:00.1; J2000) and RA, Dec = (06:12:53.1, +67:03:59.1; J2000). Some frequency channels with terrestrial radio frequency interference have been zero-weighted.

See Astronomer’s Telegram
ATEL #11902
Summary

- CHIME is a dedicated cosmology experiment designed to measure BAO in the large scale distribution of neutral hydrogen between redshifts 0.8 and 2.5.

- Challenges and uncertainties:
  - Foregrounds $10^5$ brighter than 21 cm signal.
    - Foreground avoidance and removal are active areas of research:
      - Foreground wedge (Parsons et al. 2012)
      - Karhunen-Loève filter (Shaw et al. 2014, 2015)
    - Will require characterization of the instrument at an unprecedented level.
  - Constraints will depend on HI density and bias of 21 cm sources.
    - Cosmological 21 cm signal detected in cross-correlation at $z = 0.8$ (Chang et al. 2010, Masui et al. 2013).

- CHIME is currently collecting science data.

- Experiment will reach full capacity by Fall. Survey will last 5 years.
  - Potential to yield Stage IV constraints on dark energy equation of state.
Thank you!
Check out our website at: [www.chime-experiment.ca](http://www.chime-experiment.ca)