Long wavelength astrophysics

by

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Abstract

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Acknowledgements

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Chapter 1

The Canadian Hydrogen Intensity Mapping Experiment

1.1 Chapter Overview

In this chapter we will introduce in detail the Canadian Hydrogen Intensity Mapping Experiment (CHIME).

1.2 Introduction

CHIME is a Canadian collaboration between the University of British Columbia (UBC), the University of Toronto (UofT), McGill University, and the Dominion Radio Astrophysical Observatory (DRAO). Located at DRAO near Penticton, BC, it is Canada's national radio observatory, and consists of two stages: A pathfinder instrument, known hereon as the CHIME Pathfinder, which is two 20x37 m cylinders; and the final instrument, called either full CHIME or just CHIME, and is four 20x100 m cylinders. The Pathfinder was first "on sky" in November 2013, however it has only been observing in full capacity, i.e., with all of its feeds mounted and drawing power, since XX 2015. As of late spring 2016, Full CHIME's structure exists and is meant to be instrumented before the end of 2016.

CHIME's primary science goal is to measure the Universe's neutral hydrogen, mapping out the large-scale structure (LSS) and constraining dark energy's equation of state. However, it was noticed early on that CHIME could be a powerful tool for studying several different facets of the time-variable sky. Digital radio telescopes like CHIME can run multiple experiments in parallel, since data can be siphoned off and split between different backends. In light of this an effort was made, successfully, to acquire funding

Figure 1.1: Photograph of the CHIME Pathfinder, constructed in 2013. The Pathfinder was built as a testbed for analysis and instrument design, largely because CHIME is attempting a very difficult measurement that requires an unprecedented understanding of our telescope. In attempting a new technique with an unorthodox telescope design we were guaranteed to not get it perfect the first time, hence the smaller precursor instrument to “find the path”. After two years of taking data in multiple configurations, we have learned a number of lessons about calibration, cross talk, our beams, and the correlator. We also ran into unforeseen obstacles, including a mis-pointing caused by the ambiguous definition of “north”, the pervasive effects of a standing wave betweem the reflector’s vertex and our focal line, and the impact of surface perturbations in the cylinders’ mesh.

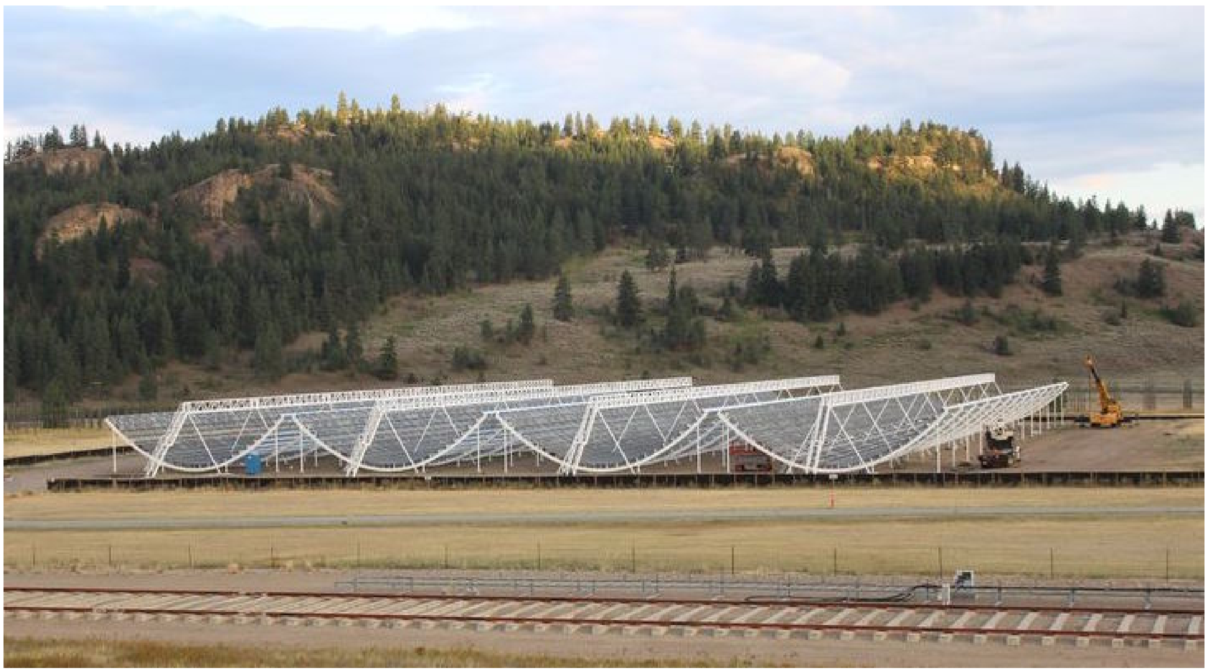

Figure 1.2: Full CHIME shortly after the construction of the fourth and final parabolic cylinder in fall 2015. Each dish is 20 m in the east-west direction and 100 m long. Unlike the Pathfinder, the cylinders are aligned with the *celestial* North Pole and should have true declination beams. There was also great care taken creating a smooth surface, since the Pathfinder's relatively large surface RMS lead to issues with its beams.

for two new experiments to piggy-back on CHIME. One is a pulsar backend that will monitor large numbers of sources, observing up to 10 pulsars at a time, 24/7. Another is an FRB backend that will search 1024 FFT-formed beams for dispersed transients.

1.3 CHIME Science

1.3.1 21 cm Cosmology

Historically, constraining the nature of dark energy has been expensive in time and resources. Probably the most promising method has been to map out the Universe's matter at large scales and many different redshifts, and measure its expansion with the BAO (Eisenstein et al., 2005; Seo & Eisenstein, 2003). Traditional spectroscopic galaxy surveys require resolving scales (of galaxies, namely, $\sim$10s of kpc) that are much smaller than the LSS, specifically the BAO ($\sim$100 Mpc). A far more economic, albeit uncharted, approach is to map out 21 cm emission from hydrogen that traces the underlying dark matter distribution (Battye et al., 2004). This technique was proposed by Chang et al. (2008) as a cheaper and more efficient alternative to galaxy surveys for probing dark energy, and it was given the name intensity mapping. Since one is concerned only with $\sim$degree angular scales, the collective emission from thousands of galaxies can be used as a proxy for the Universe's LSS, since it is thought to be a biased tracer of the dark matter.

In principle intensity mapping gives us access to large volumes of the Universe, and therefore cosmic variance limited constraints on dark energy's equation of state parameter w. However, like many high-reward, low economic-cost techniques, 21 cm intensity mapping comes with a number of systematics. Terrestrial radio frequency interference (RFI) is ubiquitous, meaning long-wavelength measurements will always be contaminated by human communication. But fundamentally, intensity mapping is difficult because the redshifted HI emission that contains the cosmological information is extraordinarily faint. Radio foregrounds below 1.4 GHz can be 10^3-10^5 times brighter than the cosmological 21 cm signal (Furlanetto et al., 2006; Morales & Wyithe, 2010). This includes Galactic synchrotron, extragalactic point-sources, and to some extent, bremsstrahlung.

The signal of interest must therefore be extracted from underneath the loud foregrounds. This would be impossible if it were not for the spectral nature of these foregrounds: Since synchrotron radiation is the sum of a continuous distribution of large numbers of relativistic electrons with different energies, the resulting spectra are smooth and well-characterized by a power-law Rybicki & Lightman (1979). On the other hand, 21 cm emission is not spectrally smooth since each frequency corresponds to a different redshift and therefore a different patch of neutral hydrogen. One can take advantage of this difference by separating the smooth and rough components of the signal in frequency space, and there have been numerous attempts at doing this effectively (Parsons & Backer, 2009; Liu & Tegmark, 2011; Shaw et al., 2015, 2014). Shaw et al. (2015, 2014) developed a statistically optimal method known as the "m-mode formalism" for foreground removal and map-making in the presence of beam uncertainties and polarization leakage. Though it was developed with CHIME in mind, it can applied to any transit interferometer. It was found by Shaw et al. (2015) that one caveat of this method is that one's telescope must be characterized with an unprecedented level of precision. Complex gains must be tracked with regular cadence, and one must know one's full-polarization beams very well. In Sect. 1.4 we detail our attempts at this characterization on the Pathfinder.

Once CHIME is calibrated at the level where foregrounds can be removed, it will go after the redshifted 21 cm emission between z =0.8-2.5, corresponding to a band of 400-800 MHz. CHIME is constructed to measure angular scales on the sky that best constrain the matter power spectrum at modes corresponding to the BAO. The first peak appears at 1.35-3° for redshifts 0.8-2.5. The smallest scales that need to be detected are set by the third peak,

1.3.2 Pulsar

1.3.3 FRB Survey

1.4 Instrument

CHIME is a novel telescope that carefully pairs its signal processing and analysis pipeline with its instrumental specifications. It is a cylindrical radio interferometer aligned in the north-south direction, and has no moving parts. As a transit telescope, it looks at the meridian as the earth rotates and the sky passes overhead, and has an on-sky duty-cycle of 100%. Since its reflectors are parabolic cylinders, light is focused only in the east-west direction, with a transverse beamwidth given by $\frac{\lambda}{D} \approx$ 1-2°. In the north-south direction the dish effectively acts as a mirror. This results in a very large declination beam that can see nearly the whole north-south sky, barring the feed's beam and cosine projection at low-elevation. To gain north-south spatial resolution, CHIME's focal line is populated with broad-band, dual-polarization antennas that we call "clover" feeds due to their four

	Pathfinder	**Full CHIME**
Geometric area	1,480 m^2	8,000 m^2
Freq	400-800 MHz	400-800 MHz
Redshift	2.5-0.8	2.5-0.8
Beamsize	2.5°-1.3°	0.43°-0.22°
No. cylinders	2 (20x37 m)	4 (20x100 m)
No. dual-pol antennas	128	1024
No. tracking beams	1	10
No. FFT beams	?	1024
No. freq channels	1024	1024 (cosm, psr), 16384 (frb)
E-W FoV	2.5°-1.3°	2.5°-1.3°
N-S FoV	$\sim$100°	$\sim$100°
Receiver Temperature	50 K	50 K

Table 1.1: CHIME Parameters

pedals. The signals from these feeds can then be interfered either in beamforming or by traditional interferometric correlation.

The clover feeds are distributed along the focal lines in groups of four, mounted to steel “cassettes”, each of which contains one power source and electronics for thermometry. The feeds are separated by $\sim$30 cm, constrained by their physical size and the requirements of a 400-800 MHz feed. This is problematic for the top of our band. Since we observe at 37.5-75 cm, wavelengths shorter than twice the physical separation of our feeds will not be properly Nyquist sampled. Therefore below $\sim$60 cm (above $\sim$500 MHz) we do not uniquely measure the electric field in the north-south direction and our signal will be aliased. In other words, without external information, a point source’s declination will be ambiguous at high frequencies.

After light bounces off the reflector and couples to the clover feeds, the signal is amplified by low-noise amplifiers (LNAs). The signal is then sent through coaxial cable down the cylinder’s central strut and into the correlator Sea Can, where all 256 feeds are fed into the RF hut. There the signals pass through a second-stage of amplification in the FLAs, before being distributed among 16 ICEboards.

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1.4.1 Beams

1.5 Pathfinder analysis

1.6 Conclusion

Acknowledgements

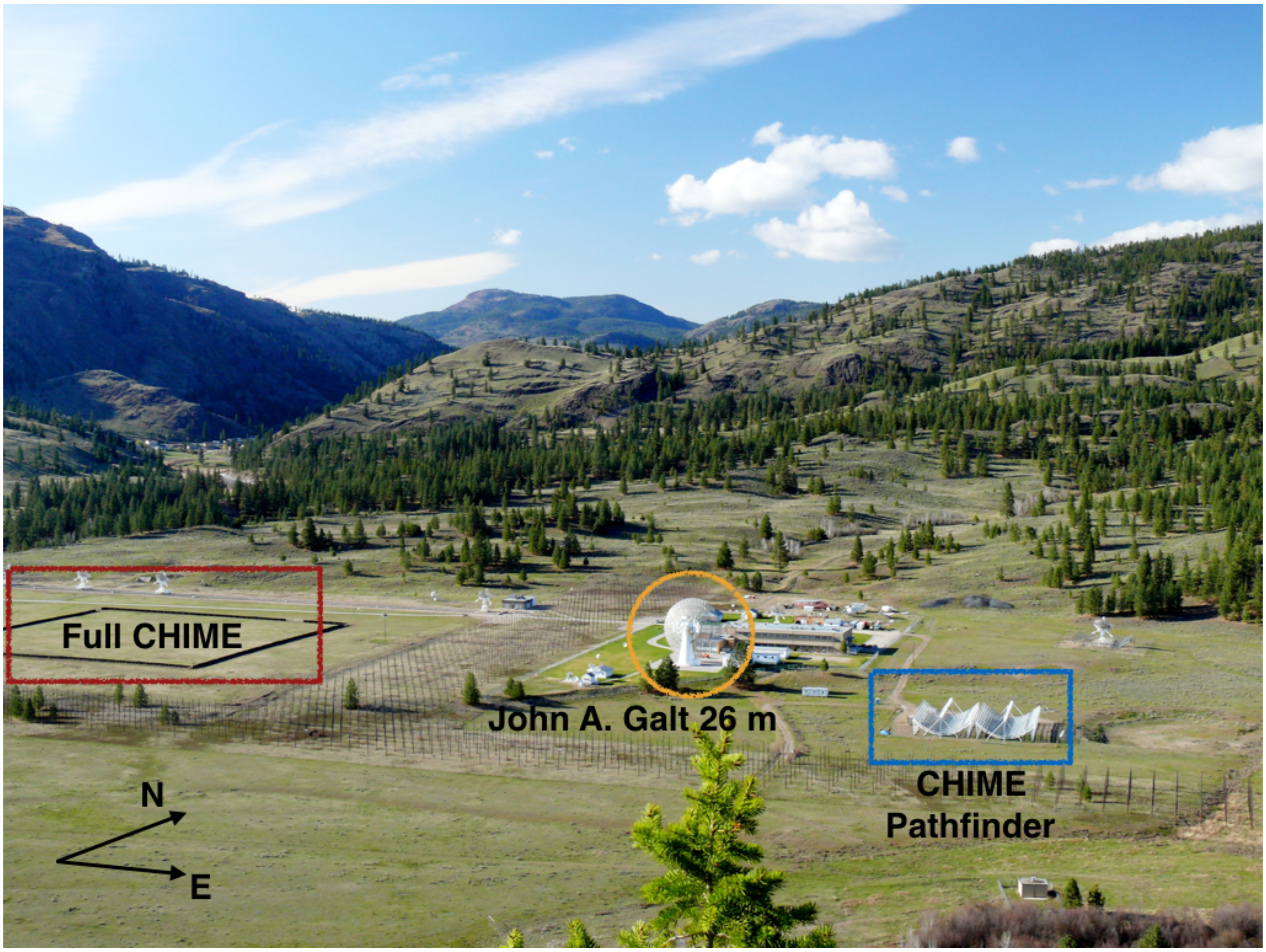
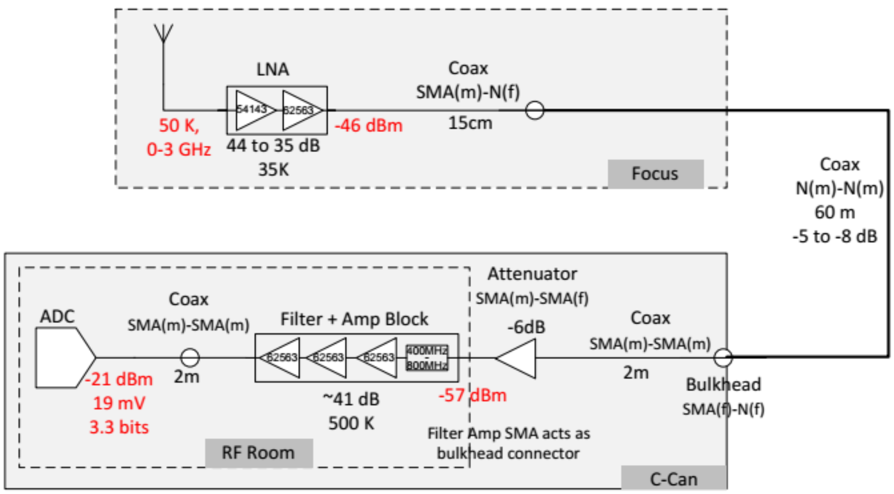


Figure 1.3: The Dominion Radio Astrophysical Observatory (DRAO) in Penticton, British Columbia. The site hosts three dishes relevant to CHIME. One is the CHIME Pathfinder. Another is the John A. Galt 26 m telescope, which is a steerable equatorial telescope that is used for holographic beam mapping of both full CHIME and its pathfinder. Finally, the full four-cylinder instrument was not constructed at the time of this photograph, but is now in the west-most field.



LNA
54143
62563
50 K,
0-3 GHz
44 to 35 dB
35K
-46 dBm
Coax
SMA(m)-N(f)
15cm
Focus
Coax
N(m)-N(m)
60 m
-5 to -8 dB
ADC
Coax
SMA(m)-SMA(m)
2m
-21 dBm
19 mV
3.3 bits
Filter + Amp Block
62563
62563
62563
400MHz
800MHz
~41 dB
500 K
-57 dBm
Attenuator
SMA(m)-SMA(f)
-6dB
Coax
SMA(m)-SMA(m)
2m
Bulkhead
SMA(f)-N(f)
Filter Amp SMA acts as
bulkhead connector
RF Room
C-Can

Figure 1.4:

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