CCAT-prime: a high throughput, high sensitivity telescope for star and galaxy formation and cosmology

Gordon Stacey
Cornell University

Representing the CCAT consortium
Who is CCAT-prime?

- Cornell University
- German consortium led by University of Cologne
  - Cologne, Bonn, Ludwig Maximilian, Max Planck Inst. for Astrophysics
    - Formed CCAT Observatory, Inc.
- Canadian consortium led by University of Waterloo
  - Waterloo, Toronto, British Columbia, Calgary, Dalhousie, McGill, McMaster, Western Ontario
    - Formed Canadian Atacama Telescope Corp (CATC)

- CCAT is a Joint Venture between CCAT Corp & CATC
What is CCAT-Prime?

CCAT-Prime is a high surface accuracy 6 m submm telescope.
Where is CCAT-prime?

Cerro Chajnantor at 5600 m
6 meters? Why are we doing this?

• Unique site enables unique science
• High accuracy (< 11 μm rms), low blockage telescope (< 1%) maximizes surface brightness sensitivity
• Extraordinary throughput optimizes for science enabled by large scale surveys
• CCAT-prime paves the way for a large (25 meter) aperture at the site
5000 meter is good, but 5600 meters is better

- Submillimeter sensitivity is all about telluric transmission
- Simon Radford ran tipping radiometers at primary sites for more than a decade –
- Simultaneous period for CCAT vs. ALMA site: median is 0.6 vs. 1 mm $\text{H}_2\text{O} \Rightarrow \text{factor of 1.7 in sensitivity}$
Median **Zenith** Transmission

ATM 2002 Model (Pardo et al.)

<table>
<thead>
<tr>
<th>Location</th>
<th>Median Conditions</th>
<th>T [K]</th>
<th>PWV [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCAT</td>
<td>5600 m (520 mb)</td>
<td>273</td>
<td>600</td>
</tr>
<tr>
<td>ALMA</td>
<td>5000 m (560 mb)</td>
<td>273</td>
<td>1000</td>
</tr>
<tr>
<td>CSO</td>
<td>4100 m (625 mb)</td>
<td>273</td>
<td>2000</td>
</tr>
<tr>
<td>SP</td>
<td>2850 m (691 mb)</td>
<td>223</td>
<td>400</td>
</tr>
</tbody>
</table>

Median CCAT transmission even better than South Pole due to warmer, less dense atmosphere.

**Tropics:** $\Omega = 3 \pi \text{ sr}, A_{\text{med}} = 1.1 (z < 60^\circ)$

**Pole:** $\Omega = 1 \pi \text{ sr}, A_{\text{med}} = 1.4 (z < 60^\circ)$
Chajnantor Site opens up the THz Windows

ATM 2002 Model (Pardo et al.)

273 K PWV

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<tr>
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<th>CCAT 10%: 5600 m (520 mb)</th>
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<th>CCAT 50%: 5600 m (520 mb)</th>
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<th>CSO 50%: 4100 m (625 mb)</th>
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<tr>
<td></td>
<td>200 μm</td>
<td>400 μm</td>
<td>600 μm</td>
<td>1000 μm</td>
<td>2000 μm</td>
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Zenith Transmission [%]

Frequency [GHz]
The CCAT-P Concept

6-meter off-axis submm telescope located at CCAT site at 5600 meters on Cerro Chajnantor

- Surface accuracy of $<10 \, \mu m$ (7 $\mu m$ goal)
- High site gives routine access to 350 $\mu m$, 10% best weather to 200 $\mu m$, advantage at longer $\lambda$s
- Novel off-axis crossed-Dragone design yielding $\Rightarrow$ wide, flat field-of-view for Galactic, Cluster, and EoR science
- Optimized throughput $\Rightarrow$ platform for as Stage 4 CMB observatory
- Plan targeted “campaign-mode” science: aperture size, throughput, mapping speed, superb site
CCAT-prime

General Layout

- Shutter
- Mirrors M1 & M2
- Elevation Housing
- Yoke Structure
- Support Cone

Being designed and built by Vertex Antennentechnik GmbH

12 June 2017
Crossed Dragone Design

Optics tubes are mostly enclosed in Strehl>0.8 (diffraction-limited)

- 3 mm = 37 OT = 26,000 pixels
- 2 mm = 33 OT = 58,000 pixels
- 1 mm = 19 OT = 110,000 pixels
- 0.35 mm = 7 OT = 400,000 pixels

M. Niemack, Applied Optics 2016
P-Cam

- Seven subcamera “tubes” populated with TES bolometers
- FoV ~ 0.9 degree with feedhorn fed 1.5 $\lambda/D$ pixels
  - 20,000 to 60,000 pixels per subcamera @ 350 $\mu$m; numbers scale from 60,000 as $1/\lambda^2$
  - dichroic polarization sensitive bolometers at longer wavelengths
- Cameras are modular (size, optics, filtration), easily exchanged
- Start with very modest numbers of pixels and growth to fill out camera, then entire CCAT-Prime FoV if so desired
CCAT-Prime Science

- **GEco:** Star formation in the Milky Way, the Magellanic clouds and other nearby galaxies through submm spectroscopy and photometry
- **kSZ:** Probing of the nature of dark energy, gravity on large scales and neutrino mass sum through kinetic SZ effect
  - Polarization foregrounds: Galactic dust science & CMB poln corrections
- **GEvo:** Evolution of DSFG through submm-mm wave surveys.
- **IM-EoR:** EoR intensity mapping in [CII] at redshifts from 5 to 9.
- **Stage 4 CMB:** CMBR polarization at 10 times the speed of current facilities ⇒ inflationary gravity waves and the sum of the neutrino masses.
**GECO: Galactic Ecology Science**

- 15” imaging over 200 ($^\circ$)$^2$ scales of the Milky Way, LMC, SMC in:
  - [CI] tracing gas temperature and mass
  - Mid and high-J CO & $^{13}$CO tracing gas excitation, shocks, density and mass
  - Also: [NII] tracing embedded SF regions and numbers of ionizing photons
- Tracing accumulation and flows of gas into cores and young stars
- Requires high site for short submm (200 μm, or 1.5 THz) studies
“CO dark” Gas
Direct observations of the most massive bound entities in the Universe through Sunyaev-Zel’dovich effects

- 7 colors: 0.35 to 3 mm spectral coverage separates out the tSZ, rSZ, radio galaxies and submm galaxies from kSZ
- Constraints: optical depth, velocity, and electron temperature

Mike Zemcov
Fundamental Physics Probes

Directly measure velocities of 1000’s of clusters

- Constrains and/or eliminate models about dark energy and modified gravity.
- Improve constraints on the measurements of the sum of the neutrino masses.
- Cluster characterization to inform cosmology
- Example Survey 1000 ($^\circ$)$^2$ measuring 3000 clusters with $M > 2.7 \times 10^{14} M_{\odot}$ in 3000 hrs

CCAT-prime velocities appear much better than Advanced ACTPol

F. de Bernardis and A. Mittal

12 June 2017
IM Workshop II, Johns Hopkins
Obscured SF over Cosmic Time

- CCAT-p aperture lowers 3.5m Herschel confusion limits
- Herschel surveys limited to ~6.3 mJy (1σ) confusion limit
- 5.5 m CCAT-p goes a factor of ~2.6 deeper into the confusion
  - 2.4 mJy (1σ) in 3 hrs @350 μm
- One camera, using best 50% weather → 100°² (or 300°²!) survey @ 350 μm per year
- Pushes down the luminosity function in the most active epoch star formation in the Universe

HerMES Lockman Hole North; Oliver et al. (2010, 2011)
CCAT-prime and Herschel

Herschel confusion limited

CCAT-prime confusion limited

10 arcmin

350um

Courtesy of B. Magnelli
CCAT-p Explores FIR Luminosity Function

**Graph Description:**
- **X-axis:** Redshift (z)
- **Y-axis:** Star Formation Rate ($M_\odot$ yr$^{-1}$)
- **Z-axis:** IR-luminosity ($L_\odot$)
- **Age of Universe:** [Gyr]

Key Features:
- **CCAT-p:** 4000 deg$^2$ survey, ~2000 hrs
- **ALMA-350μm:** 2 deg$^2$, ~2000 hrs
- **ALMA-350μm:** 0.05 deg$^2$, ~2000 hrs
- **Herschel SPIRE:** 2 deg$^2$, confusion limit

Legend:
- $L^+$

Note: Not accessible by 4000 deg$^2$, 2 deg$^2$, 0.05 deg$^2$ surveys.

**Courtesy of B. Magnelli**

12 June 2017
IM Workshop II, Johns Hopkins
EoR-IM: Intensity Mapping of [CII] in the Epoch of Reionization

• Aggregate [CII] signal from star forming galaxies at $z \sim 5$ to 9 $\Rightarrow$ 3-D information:
  - Reveals the process of reionization and the underlying dark matter distribution over the cosmic time when the first galaxies formed

• Combine with SKA 21 cm HI line tracing neutral ISM concentrations

Simulating Reionization

Reionization appears not to occur instantaneously, but rather depends on local density (see Finlator et al. 2009). First things to reionize are overdense regions, then voids, then moderate-density structures.
Intensity Mapping of [CII] from the EOR

- Measure large scale spatial fluctuations of collective aggregate of faint galaxies via redshifted [CII] 158 µm line (+possibly other lines at other z’s)
  - Resolution into individual galaxies not required
    - Clustering scale 0.5 to 1 Mpc or ~1-2’ at z = 5-9, - good match for 6-m aperture (40”@ 1mm)
    - 16°² surveys: spectral/spatial mapping speed critical
    - FoV ~ > 1° matches 40 Mpc void size-scale: systematics
    - Need moderate spectral resolution R ~ 300-500

- Bandwidth of z ~ 5-9 signal is 0.95-1.6 mm (190-315 GHz)
  - Identify interloper lower z CO by line multiplicity – complete at z > 0.8
  - Sensitivity is at a premium: high site, very low emissivity telescope is essential!
Prediction of the [CII] Signal Strength

Gong et al 2012

Noise requirement = $8 \times 10^{-14}$ W/m$^2$/sr

<table>
<thead>
<tr>
<th>Aperture diameter (m)</th>
<th>1</th>
<th>3</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey Area ($A_s$; deg$^2$)</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Total integration time (hours)</td>
<td>4000</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>Free spectr</td>
<td>185–310</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freq. resol</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of bolometers</td>
<td>20,000</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Number of spectral channels</td>
<td>312</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>Number of spatial pixels</td>
<td>64</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Beam size ($\theta_{beam}$; FWHM, arcmin)</td>
<td>4.4</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Beams per survey area</td>
<td>$2.6 \times 10^3$</td>
<td>$2.3 \times 10^4$</td>
<td>$2.6 \times 10^5$</td>
</tr>
<tr>
<td>$\sigma_{pix}$: Noise per detector sensitivity ($\text{Jy}\sqrt{s}/\text{sr}$)</td>
<td>$2.5 \times 10^6$</td>
<td>$2.5 \times 10^6$</td>
<td>$2.5 \times 10^6$</td>
</tr>
<tr>
<td>$t_{obs}^a$: Integration time per beam (hours)</td>
<td>100</td>
<td>11</td>
<td>1.0</td>
</tr>
<tr>
<td>$z = 6 V_{pix}$ (Mpc/h)$^3$</td>
<td>217.1</td>
<td>24.1</td>
<td>2.2</td>
</tr>
<tr>
<td>$z = 7 V_{pix}$ (Mpc/h)$^3$</td>
<td>332.9</td>
<td>37.0</td>
<td>3.3</td>
</tr>
<tr>
<td>$z = 8 V_{pix}$ (Mpc/h)$^3$</td>
<td>481.3</td>
<td>53.5</td>
<td>4.8</td>
</tr>
<tr>
<td>$z = 6 P_N^{\text{CII}}$ (Jy/sr)$^2$ (Mpc/h)$^3$</td>
<td>$5.4 \times 10^9$</td>
<td>$5.4 \times 10^9$</td>
<td>$5.3 \times 10^9$</td>
</tr>
<tr>
<td>$z = 7 P_N^{\text{CII}}$ (Jy/sr)$^2$ (Mpc/h)$^3$</td>
<td>$4.8 \times 10^9$</td>
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\textit{a} values computed at 238 GHz, corresponding to CII at $z = 7$.  

RP = 500
Large BW × FoV Spectrometer

• Trans-mm wave from ~ 0.95 to 1.6 mm (315-188 GHz)
• Direct detection for optimal sensitivity
• Resolving power requirement is modest, ~ 500 or 600 km/sec
• Need a spectral × spatial product > 20,000 to complete a 16°² survey in 4000 hours.
• Spectrometer extremes:
  – 312 spectral positions, 64 spatial positions w/ grating
  – 1 spectral sample, 20,000 spatial positions w/ FPI
EoR IM Science Program

• The spectral multiplexer is challenging at present
• The spatial multiplexer is very straight-forward
• Requirement: One third (or even $1/6^{th}$) the number of pixels of grating

Predictions: 9 $1/6^{th}$ the number of pixels of grating

Using 3.2 cameras tuned to 1.1 and 1.4 mm wavelengths, we can survey a $16^{°2}$ field to the required $1$ s noise limit of $8 \times 10^{-14}$ W/m$^2$/sr in $4000$ hours integration time.

Total number of pixels: $3.2 \times 1050$ (dichroic) or $6.4 \times 1050$ single color
A Tough Experiment!

• The zenith transmission is:
  – 97.9 to 96.6% at our site
  – 96.9 and 95.1% at ALMA site

• Telescope emissivity is 2%
  – Going off-axis makes a difference!

• System emissivity is ~ 5.9%
  – Going to 5600 m makes a difference!
    • Would need 4.1 compared with 3.2 tubes
  – Window emissivity makes a difference (2%)

• Spectrometer transmission is 40% including DQE of 80%
  Note that the same stringent requirements hold for the grating spectrometer

IM Workshop II, Johns Hopkins
Fabry-Perots in Development

$R = 10^6$ FPI at 112 um for HIRMES on SOFIA

- These are based on free-standing metal mesh
- Developing silicon substrate-based FPI:
  - Silicon AR coatings (dual layer) with microstructures
  - Metalized (superconducting) broad-band reflectors
Comparisons to other Coeval Facilities

- **EoR IM**: surface brightness: WFE, emissivity, site, and FoV:
  - Sensitivity (Jy/beam) $\propto$
    - 1/Ruze Efficiency
    - $\sim (\text{System Emissivity})^{1/2}$ – telescope, warm optics and sky
    - 1/(warm transmission) – includes telescope efficiency, sky transparency
  - Mapping Speed $\propto$
    - (Sensitivity referred to EOR beam)$^2$
    - Field of view accepted/field of view of P-Cam subcamera

<table>
<thead>
<tr>
<th>Teles.</th>
<th>WFE (rms), Ruze eff.</th>
<th>Med. PWV</th>
<th>$\eta_{\text{sky}}$ (245 GHz)</th>
<th>tel. emis.</th>
<th>Raw Sens.$^2$</th>
<th>P-Cam FoV</th>
<th>FoV (dia.)</th>
<th>Mapping Speed</th>
</tr>
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<tbody>
<tr>
<td>APEX</td>
<td>17 $\mu$m, 97%</td>
<td>1.0</td>
<td>0.945</td>
<td>10%</td>
<td>0.86</td>
<td>24.8’</td>
<td>11.4’</td>
<td>1/16</td>
</tr>
<tr>
<td>JCMT</td>
<td>25 $\mu$m, 93%</td>
<td>2.0</td>
<td>0.901</td>
<td>10%</td>
<td>0.93</td>
<td>19.8’</td>
<td>9.0’</td>
<td>1/28</td>
</tr>
<tr>
<td>LMT</td>
<td>70 $\mu$m, 58%</td>
<td>2.0$^1$</td>
<td>0.901</td>
<td>15%</td>
<td>0.51</td>
<td>5.9’</td>
<td>8.0’</td>
<td>1/77</td>
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<tr>
<td>CCAT-p</td>
<td>10.5 $\mu$m, 99%</td>
<td>0.60</td>
<td>0.962</td>
<td>2.8%</td>
<td>1</td>
<td>54’</td>
<td>143</td>
<td>1$\rightarrow$7</td>
</tr>
</tbody>
</table>

$^1$This weather is only 4 months/year; $^2$Refers to a 65” beam and source elevation of 50°
**Comparisons to other Coeval Facilities**

- **kSZ; GEvo:** short submm bands: WFE, emissivity, site, and FoV:

  **Point source foregrounds**

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<tr>
<th>Teles.</th>
<th>WFE (rms), Ruze eff.</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Q PWV</th>
<th>( \eta_{\text{sky}} ) (860 GHz)</th>
<th>tel. emis.</th>
<th>Raw Sens.(^2)</th>
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<td>0.12</td>
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<td>1.31</td>
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<td>9.0’</td>
<td>1/8.3(^3)-1/56(^4)</td>
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<tr>
<td>LMT</td>
<td>50 ( \mu \text{m}, ) 4%</td>
<td>1.0(^1)</td>
<td>0.12</td>
<td>15%</td>
<td>1.47</td>
<td>5.9’</td>
<td>8.0’</td>
<td>1/8.6(^3)-1/640(^4)</td>
</tr>
<tr>
<td>CCAT-p</td>
<td>10.5 ( \mu \text{m}, ) 87%</td>
<td>0.4</td>
<td>0.39</td>
<td>2.8%</td>
<td>1</td>
<td>54’</td>
<td></td>
<td>1→7</td>
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\(^1\)This weather is only 4 months/yr; \(^2\) **Point source** – el. = 50°; \(^3\)beams, \(^4\)areal coverage

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**1’-scale kSZ Science**

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Schedule

Four (4) year project (July 2017 to June 2021)
- 20 months Detailed Design  [PDR @ 4 mths; CDR @ 10 months, FDR @ 18 months.]
- 13 months Fabrication which includes a Trial Assembly in Germany
- 3 months Shipping & Receiving
- 12 months Assembly/Checkout
  - Incl. 3 months unpacking/inspection and sequenced transport to Summit