CCAT: Project Overview, Science & Instrumentation Plans

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What is CCAT?

• A 25-meter FIR/submillimeter telescope that will operate at wavelengths as short as $\lambda = 200 \mu$m, an atmospheric limit

• To be located in a high (5617m) desert environment

• Designed to take advantage of one of the fast-developing detector technologies, opening up for surveys one of the last, largely untapped frontiers of ground-based astronomical research

Beam size: $\lambda [\mu m]/100$ arcsec
e.g. 2” @ 200 $\mu$m

FoV: 1 sq. deg.

Half WF err: 9.5 $\mu$m rms (goal)

Continuum
Sensitivity, 5$\sigma$, 1 hr : 1 mJy
@ 350 $\mu$m

First-light
short $\lambda$ camera: 50 kpix

Several instruments in Nasmith foci
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Why 25m?
- Match ALMA sensitivity in submm regime
- Integration time to confusion at $350 \mu m \sim 1$ hr or to fully resolve the FIR/submm CBR
- Better than 0.5” source positioning

Beam size: $\lambda[\mu m]/100$ arcsec e.g. 2” @ 200 $\mu m$

FoV: 1 sq. deg.

First-light short $\lambda$ camera: 50 kpix

Several instruments in Nasmith foci
What is CCAT?

CCAT is intended to be run in the mode of a “university radio observatory” by a consortium of mostly academic partners.

- Strong emphasis on facility as training ground for the instrumentalists, observers, telescope makers of tomorrow
- Exploit single dish flexibility to respond rapidly to new discoveries and in testing new technologies
- “Lean & mean” bureaucracy and goal to release its data with short “proprietary periods”, in order to maximize science fall-out.

**Current CCAT partners:**
- Cornell University
- California Institute of Technology & NASA JPL
- University of Colorado
- University of Cologne
- University of Bonn
- Canadian university consortium: Univs of British Columbia, Calgary, Dalhousie, McGill, McMaster, Toronto, Waterloo, Western Ontario
- Associated Universities, Inc.
- + others (discussions on-going)
Principal CCAT Science Themes

• Determine the history of galaxy formation through its earliest times by resolving the far infrared background and measuring the molecular gas, dust masses and star formation rates for millions of typical \((L < L_*)\) galaxies
• Establish the primary environmental factors that govern the rate and efficiency of star formation by measuring the structure and kinematics of Giant Molecular Clouds at the resolution of individual dense cores
• Obtain a complete picture of the energy budget in galaxy clusters by combining measurements of the gas thermal pressure, internal motions and temperature with multiwavelength probes to characterize the evolution of galaxy clusters via mergers, accretion and energy injection
Over cosmic time, half of the radiation emitted by stars has been absorbed by dust and re-emitted at FIR and submm wavelengths.

- Dust reprocesses starlight into FIR
- Cosmic expansion shifts light of early galaxies further into submm and mm bands

Lagache, Puget, & Dole 2005
CCAT will have the sensitivity and angular resolution to resolve the CFIRB and measure the properties of individual galaxies on scales and flux levels that are impossible with existing or planned FIR observatories.
Galaxy Counts and the Cosmic FIRB at Submm Wavelengths

- ~10% of CFIRB resolved directly with Herschel
- ~50% inferred statistically, yielding estimated number count models to a depth of 2 mJy/beam
- **CCAT will resolve (directly) sources to 0.5-1 mJy, likely resolving the totality of the CFIRB**
- ➤ **Large Scale surveys into the most active epoch of assembly of cosmic structures**

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The Origin of Stars

Spitzer and Herschel composite IR image (8, 24 and 70 μm) at 6″ resolution of a 0.7° x 2° region of the Galactic Plane. The IR data trace the location and luminosity of embedded stars.

CCAT will observe the cold dust, molecular lines and atomic lines at comparable (or better) angular resolution to measure the spatial structure, kinematics, distances and masses of the molecular clouds. The combined data sets will empirically establish the primary factors that influence the star formation rate and efficiency in molecular clouds.
The Formation of Galaxy Clusters

CCAT’s high angular resolution and multiwavelength coverage is needed to spatially resolve the cluster, remove galaxy contamination and separate the distinct SZ signals.

CCAT observations in multiple bands, indicated by colored bars, will measure the thermal (dash red), relativistic (dashed orange) and kinetic (dash blue) SZ contributions to the surface brightness spectrum of an individual cluster.

CCAT’s high angular resolution and multiwavelength coverage is needed to spatially resolve the cluster, remove galaxy contamination and separate the distinct SZ signals.
Synergy with ALMA

ALMA will deliver very high spatial resolution, but only over a very small Field of View:

➤ Will reveal fine detail, **ONE SOURCE AT A TIME**

CCAT will not match ALMA in angular resolution (beam 2”-5” will not yield morphological info); it will however match it in continuum sensitivity and will have a Field of View 30,000 times larger

➤ **FAST SURVEYOR** (many objects at a time)
Figure 2: Field-of-view of the CCAT telescope (1°) and the first-light continuum camera (SWCam; 7 subcameras with 6′ field-of-view each) compared with other submillimeter telescopes that operate at 350 μm or 450 μm. CCAT’s large field-of-view enables efficient surveys and anticipates continued growth in detector array size.

Figure 3: Comparison of CCAT’s continuum wide-field imaging sensitivity with other submillimeter telescopes. The 5σ detection limit is for a 1 hour survey over a 1 deg² area on the sky. Also shown is the predicted CCAT extragalactic confusion limit for 30 beams per source. CCAT will have superior capabilities to obtain deep, high resolution images over large areas.
CCAT: At the driest, high altitude site you can drive a truck to....
Median 350 μm atm. Transparency at CCAT site is 1.64x higher than at ALMA Plateau.
Figure 1: Atmospheric transmission for exceptional (10%), excellent (25%), and median conditions at CCAT and for median conditions at ALMA and on Mauna Kea [61]. The precipitable water vapor (PWV) distributions were determined from 350 μm tipper measurements [62].
Instrumentation Plans

First light: (modified) SWCam + CHAI
First generation: SWCam, CHAI, LWCam, X-Spec
Short Wavelength Camera (SWCam)

Figure 10: The right panel shows a schematic SWCam side view (light enters from the left); the left panel shows the front view with its arrangement of sub-cameras. The optical elements are anti-reflection coated high purity silicon.

Table 1: SWCam Sensitivity and Mapping Speed

<table>
<thead>
<tr>
<th>Band ((\mu m))</th>
<th>Beam Size (arcsec)</th>
<th>Pixel Count</th>
<th>Equivalent Field-of-view Diameter (arcmin)</th>
<th>NEFD per beam (mJy (\sqrt{s}))</th>
<th>Confusion Limit (mJy)</th>
<th>Mapping Speed to Confusion Limit (5(\sigma)) (deg(^2) / year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>3.5</td>
<td>4 (\times) 11,900</td>
<td>12</td>
<td>14</td>
<td>1.04</td>
<td>30</td>
</tr>
<tr>
<td>450</td>
<td>4.5</td>
<td>7200</td>
<td>6</td>
<td>10</td>
<td>1.50</td>
<td>31</td>
</tr>
<tr>
<td>850</td>
<td>8.6</td>
<td>2000</td>
<td>6</td>
<td>6.8</td>
<td>1.03</td>
<td>66</td>
</tr>
<tr>
<td>2000</td>
<td>20</td>
<td>360</td>
<td>6</td>
<td>1.9</td>
<td>0.23</td>
<td>45</td>
</tr>
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</table>

Notes: The NEFD calculations assume the top 33% weather statistics (PWV < 0.43 mm) for the 350 and 450 \(\mu m\) bands and the top 75% weather statistics (PWV < 1.49 mm) for the 850 and 2000 \(\mu m\) bands. The confusion limit is defined as 30 beams/source and was computed using the Bethermin models [5]. The area mapped in a year assumes 3550 hours available, and is adjusted by weather statistics.
CCAT Heterodyne Array Instrument (CHAI)

High-resolution spectrometer that features 2 focal plane heterodyne detector arrays that can observe simultaneously. Each array will have 64 spatial elements (goal of 128).

Table 2: CHAI specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>870 $\mu$m(*)</th>
<th>610 $\mu$m</th>
<th>370 $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel arrangement</td>
<td>8 $\times$ 8</td>
<td>8 $\times$ 8</td>
<td>8 $\times$ 8</td>
</tr>
<tr>
<td>Frequency range [GHz]</td>
<td>330–350</td>
<td>455–495</td>
<td>800–820</td>
</tr>
<tr>
<td>DSB receiver noise [K]</td>
<td>&lt; 40</td>
<td>&lt; 50</td>
<td>&lt; 130</td>
</tr>
<tr>
<td>SSB T$_{sys}$ [K]</td>
<td>179</td>
<td>667</td>
<td>1145</td>
</tr>
<tr>
<td>Spectral resolution [km/s]</td>
<td>0.054</td>
<td>0.038</td>
<td>0.023</td>
</tr>
<tr>
<td>Bandwidth [km/s]</td>
<td>3480</td>
<td>2440</td>
<td>1480</td>
</tr>
<tr>
<td>Beam size ['']</td>
<td>8.7</td>
<td>6.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Beam spacing ['']</td>
<td>22.6</td>
<td>16.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Field of view ['']</td>
<td>180 $\times$ 180</td>
<td>132 $\times$ 132</td>
<td>76 $\times$ 76</td>
</tr>
</tbody>
</table>

Notes: The single sideband (SSB) temperatures were computed for a source at 60° elevation and a zenith precipitable water vapor corresponding to the 50% (870 $\mu$m) and 25% (610 $\mu$m, 370 $\mu$m). (*) Intended to be available at first light as an additional channel.

Figure 12: CHAI optics layout. The two dewars, each with two refrigerators, are at the left. The orthogonally linearly polarized beams are combined by a wire grid polarizer, and couple to the telescope optics on the right.
Long Wavelength Camera (LWCam)

Covers 6 bands across entire FoV between 750 μm to 3.3 mm. Will benefit from developments for SWCam.

Table 3: LWCam Sensitivity and Mapping Speed

<table>
<thead>
<tr>
<th>Band (μm)</th>
<th>Beam Size (arcsec)</th>
<th>Pixel Count</th>
<th>Equivalent Field-of-view Diameter (arcmin)</th>
<th>NEFD per beam (mJy/√s)</th>
<th>Confusion Limit (mJy)</th>
<th>Mapping Speed to Confusion Limit (5σ) (deg²/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>7.5</td>
<td>10,864</td>
<td>15.6</td>
<td>8.7</td>
<td>1.37</td>
<td>508</td>
</tr>
<tr>
<td>860</td>
<td>8.7</td>
<td>10,864</td>
<td>18.2</td>
<td>6.3</td>
<td>1.03</td>
<td>737</td>
</tr>
<tr>
<td>1050</td>
<td>11</td>
<td>2716</td>
<td>11.5</td>
<td>2.6</td>
<td>0.78</td>
<td>991</td>
</tr>
<tr>
<td>1300</td>
<td>13</td>
<td>2716</td>
<td>13.6</td>
<td>2.4</td>
<td>0.59</td>
<td>930</td>
</tr>
<tr>
<td>2000</td>
<td>20</td>
<td>679</td>
<td>10.4</td>
<td>2.2</td>
<td>0.23</td>
<td>100</td>
</tr>
<tr>
<td>3300</td>
<td>32</td>
<td>679</td>
<td>16.7</td>
<td>2.0</td>
<td>0.08</td>
<td>40</td>
</tr>
</tbody>
</table>

Notes: The confusion limit is defined as 30 beams/source and was computed using the Bethermin models [5]. The area mapped in a year assumes 3550 hours available, and is adjusted by weather statistics assuming 75% of telescope time is suitable for work in the LWCam bands. Sensitivity estimates for LWCam and SWCam will not necessarily agree since the two cameras will differ in parameters such as optical transmission, telescope illumination, point source coupling, and detective bandwidth.
**X-Spec: broadband, multiobject spectrograph**

Figure 13: X-Spec On-Chip Spectrometer: Upper left: filterbank schematic; center: portion of a prototype chip. Radiation propagates down a niobium microstrip transmission line; each spectral channel consists of a detector coupled through a half-wave section of transmission line. The coupling (shown as purely capacitive for simplicity) is through proximity and is tuned through electromagnetic simulations. The large vertical structures in the chip image are the KID interdigitated capacitors. Lower left: FTS spectrum from a typical channel on the prototype chip. Channel yield is high, and the measured FWHMs are between 200 and 900, close to the design values. Out-of-band response and channel-to-channel cross talk are less than $10^{-3}$, meeting X-Spec requirements. Right: full instrument design. Eighty five backend modules are mounted to the 1K plate, each coupling a single beam from the sky into 4 spectrometer chips (2 polarizations × 2 bands). Each module couples through the radiation shields and vacuum shell to a positioner (not shown) which steers the beam within a 2-D patrol region on the sky.
Project Timeline

- October 2003: Partnership Workshop in Pasadena
- Feb 2004: MOU signed by Caltech, JPL and Cornell
- 2006-2010: Feasibility Study Review, Consortium consolidation, Site selection completed
- 2010: First-ranked mid-scale project by Astro2010
- 2010-2011 Jun: NSF Award of $4.5M toward CCAT Engineering Design, UKoeln/Bonn awarded $9M by German Research Foundation, single donor (F. Young) donation of $13M
- 2011-2013: Detailed Engineering Design (EDP) (completed)
- mid-2013: Program Design Review (PDR) (completed)
- Jan 2014: Chilean govt grants concession to land
- 2014: Finalize design, build access road, get ready (in progress)
- 2015-2019: Construction and First Light

“Patience, n. A minor form of despair, disguised as a virtue.” Ambrose Bierce
CCAT is a groundbreaking submillimeter telescope that will be located at 5600 m altitude on Cerro Chajnantor in the Andes mountains of northern Chile. CCAT will combine high sensitivity, a wide field of view, and a broad wavelength range to provide an unprecedented capability for deep, large area multicolor submillimeter surveys. Science objectives include galaxy formation and evolution throughout the history of the Universe, the hot gas pervading clusters of galaxies, star formation, protoplanetary disks, and the first light in the Universe.