CCAT
Gordon Stacey
Cornell University
CCAT Scientific Inspiration

• Measure the star and characterize the history of star formation in galaxies through cosmic time
  – Photometric surveys to resolve the FIR background
  – Spectroscopic surveys characterizing the energy sources: stellar populations, shocks and AGN activity
• Probe the astrophysics of galaxy clusters through the Sunyaev-Zel’довich effect (S-Z)
• Characterize the star formation process locally through submm-wave spectroscopy and dust continuum emission
  – Over 10’s of degree scales and through 5 orders of magnitude in scale for in the Milky Way
  – Complete maps over a variety of environments in nearby resolved galaxies
CCAT Implementation

Requirements:

• 25 meter telescope
• high surface accuracy (10 μm RMS goal)
• superb astronomical site: Cerro Chajnantor at 5617 m

– Resolves the CIRB
– Beam $\sim \lambda (\mu m/100)$ (″)
– Enables accurate astrometry for follow-up
– Can reach the confusion limit at 350 μm in a few hours
– Point source sensitivity comparable to ALMA in short submm bands:
  
  \textit{discovery and follow-up}
CCAT Implementation

Requirements:
• 25 meter telescope
• high surface accuracy (10 µm RMS goal)
• superb astronomical site: Cerro Chajnantor at 5617 m
  – Highly accessible
• Wide (1°) field of view
• 20 year lifetime

– Takes advantage of technological innovations
– Look towards future with growth of detector technology
– Simultaneous mounting and use of instrumentation
One million pixels will Nyquist-sample the 1° CCAT FoV at 350 µm

Should reach this level before the 40 years celebration...
Telescope Design

- Aperture: 25 m
- Wavelength: 350 µm – 3300 µm (200 µm goal)
  - Beam size: 3.5 arcsec @ 350 µm
- Field of view: 1° circular
- Half Wave Front Error: < 12.5 µm rms
- Gregorian optics, Nasmyth instruments
- Active primary mirror
  - Al tiles on CFRP subframes, CFRP/invar truss
  - Open loop design, provision for closed loop
- Insulated steel Az/El mount, fast scan speed
- Enclosure: protection from wind, Sun
CCAT Rear View

Primary, secondary, tertiary & instruments

Inner pier

(x6) Spokes

Outer pier

Footing

Rear iso-view @ 20 degree elevation
CCAT Side Views

- Aplanatic Gregorian
- CFRP Tripod

- Rear view @ zenith
- Side view @ 20 degree elevation
The Site: the driest, high altitude site to which one can drive a truck to...
Looking *Down* on the ALMA Site
Why the Extra 600 Meters?

- Submillimeter sensitivity is all about telluric transmission
- Simon Radford has been running tipping radiometers at primary sites for more than a decade –
- Simultaneous period for CCAT vs. ALMA site: median is 0.6 vs. 1.0 mm H$_2$O $\Rightarrow$ factor of 1.4 in sensitivity
Median Conditions

ATM 2002 Model (Pardo et al.)

\[ \Omega = 3 \pi, \quad A_{med} = 1.1 \quad (z < 60^\circ) \]

Median CCAT transmission even better than the pole due to warmer, less dense atmosphere

Median conditions

<table>
<thead>
<tr>
<th>Site</th>
<th>Altitude [m]</th>
<th>Pressure [mb]</th>
<th>Temperature [K]</th>
<th>PWV [\mu m]</th>
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<tbody>
<tr>
<td>CCAT</td>
<td>5600</td>
<td>520</td>
<td>273</td>
<td>600</td>
</tr>
<tr>
<td>ALMA</td>
<td>5000</td>
<td>560</td>
<td>273</td>
<td>1000</td>
</tr>
<tr>
<td>CSO</td>
<td>4100</td>
<td>625</td>
<td>273</td>
<td>2000</td>
</tr>
<tr>
<td>SP</td>
<td>2850</td>
<td>691</td>
<td>223</td>
<td>400</td>
</tr>
</tbody>
</table>

Pole: \[ \Omega = 1 \pi, \quad A_{med} = 1.4 \quad (z < 60^\circ) \]
Top 10% Opens up THz Windows

ATM 2002 Model (Pardo et al.)

\[ \Omega = 3 \pi, A_{med} = 1.1 \ (z < 60^\circ) \]

<table>
<thead>
<tr>
<th></th>
<th>CCAT 10%</th>
<th>CCAT 25%</th>
<th>CCAT 50%</th>
<th>ALMA 50%</th>
<th>CSO 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>5600</td>
<td>5600</td>
<td>5600</td>
<td>5000</td>
<td>4100</td>
</tr>
<tr>
<td>Pressure (mb)</td>
<td>520</td>
<td>520</td>
<td>520</td>
<td>560</td>
<td>625</td>
</tr>
<tr>
<td>PWV (\mu m)</td>
<td>200</td>
<td>400</td>
<td>600</td>
<td>1000</td>
<td>2000</td>
</tr>
</tbody>
</table>

\(273\) K

Zenith Transmission [%]

Frequency [GHz]
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- Characterize the star formation process through submm-wave spectroscopy and dust continuum emission
  - Over large scales and through 5 orders of magnitude in scale for in the Milky Way
  - Complete maps over a variety of environments in nearby resolved galaxies
Half the optical light of stars and AGN produced over the history of the Universe is absorbed by dust and re-radiated in the FIR band.
CCAT Characterizes Luminosity

CCAT measures the $L_{\text{FIR}}$ for star forming galaxies at $z > 1$

- For most cases this is:
  - Nearly the bolometric luminosity
  - Good estimate for star formation rates
  - Note that 850 $\mu$m flux is insensitive to $z$, whilst 350 $\mu$m flux is quite sensitive

Red-shifted SEDs from Paul van der Werf’s web-page
Confusion

• The large CCAT aperture breaks the confusion limit

• Herschel surveys limited to ~25 mJy confusion limit ⇒ resolve the CIRB at 10% level

• Statistically inferred at 50% level to 2 mJy/beam

• 25 m CCAT resolves directly sources at ~0.5 to 1 mJy level in few hours at 350 μm

• → large (10-40(°)²)/yr surveys into the most active epoch of assembly of galaxies and large scale structures in the Universe

• ~ million sources/year
Confusion: 25 m vs. 3.5 m telescopes

350 µm

Herschel

CCAT Beam (3.5"")

ALMA FoV (7"")

CCAT

Half SWCam FoV
Identifying the Highest Redshift Sources: 350 µm Drop-outs

>5σ 850 µm detection, 350 µm non-detections, or “drop-outs”
Spectroscopic Redshifts

• Determined with multi-object, large bandwidth, direct detection spectrometers
  – Spacing of CO lines: 115 GHz/(1+z)
  – FIR fine structure lines, especially [CII]

• Most sources detectable in the continuum are detectable in the [CII] line (if transmitted):
  – For $L_{[\text{CII}]}/L_{\text{FIR}} = 10^{-3}$; [CII]/158 $\mu$m continuum $\sim 10:1$
  – Photometric BW/Spectroscopic BW $\sim 1000/10$
  – $\Rightarrow$ sensitivity ratio $\sim \sqrt{1000/10} = 10:1$
  – $\Rightarrow$ line is as detectable as the continuum

• CO lines roughly 5 times harder to detect, but the detection of multiple lines helps significantly
Spectroscopy

- X-Spec: a very broad (50%) BW spectrometer
- [CII] much easier to detect...
- Multiple CO lines help, and uniquely determine the redshift

<table>
<thead>
<tr>
<th>Redshift</th>
<th>L(FIR)</th>
<th>Line</th>
<th>SNR</th>
</tr>
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<tbody>
<tr>
<td>1.15</td>
<td>$8 \times 10^{11}$</td>
<td>[CII]</td>
<td>75</td>
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<tr>
<td></td>
<td></td>
<td>CO(6-5)</td>
<td>12</td>
</tr>
<tr>
<td>1.85</td>
<td>$8 \times 10^{11}$</td>
<td>[CII]</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO(6-5)</td>
<td>4</td>
</tr>
<tr>
<td>6.3</td>
<td>$2 \times 10^{12}$</td>
<td>[CII]</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[NII] 205 µm</td>
<td>6</td>
</tr>
</tbody>
</table>

ALMA 5 to 10 times more sensitive per spectral tuning, but:
- Several tunings necessary
- CCAT spectrometer is multi-object

⇒ Can be more efficient with CCAT spectrometer
Physical Properties

- CO SED constrain molecular gas mass reservoir and the sources of gas heating
  - PDR heating
  - Cosmic rays
  - Micro-turbulent shocks: mid-J
  - XDR heating: high-J
- FIR fine-structure lines constrain physical parameters of the gas and the stellar radiation fields

van der Werf et al. 2010

Mrk 231

van der Werf et al. 2010
Fine-Structure Line Science

- [CII] mostly arises in PDRs on neutral clouds exposed to stellar FUV
- [CII]/FIR yields the *intensity* of the ambient FUV radiation field, $G_0$
- Observed FIR intensity is connected to the modeled $G_0$ by the beam filling factor $\Rightarrow$ the [CII]/FIR ratio indirectly yields the *size* of star formation regions
- Survey found star formation occurs on several kpc scales enveloping redshift 1-2 star forming galaxies

Contours are [CII]/FIR

Hailey-Dunsheath et al. 2010, Stacey et al. 2010
[OIII]/[NII] yields hardness of the radiation field $\Rightarrow$ Age of starburst

[NII]/[CII] yields fraction of [CII] from HII regions (Oberst et al. 2006), or with other F-S lines and FIR, metalicity

Ferkinhoff et al. 2011
Nagao et al. 2012
Instrumentation Plans

Four instruments are in preliminary design phase, all multi-institutional:

- Short Wavelength Camera (PI: G. Stacey, Cornell) (*)
- Long Wavelength Camera (PI: S. Golwala, Caltech) (*)
- Direct Detection MOS (PI: M. Bradford, JPL) (*)
- Heterodyne Feed Array (PI: J. Stützki, Köln)

(*) Direct detection instruments MKIDs are technology of choice: they are intrinsically multiplexable, and can be implemented into large format arrays with relatively simple readout electronics.

432 pixel TiN MKID array for MAKO/SWCam (Caltech/JPL)
Short Wavelength Camera (SWCam)

- 7 planar subarrays ~ 8000 pixels each @ 2.9” p.s. ⇒ 56,000 pixel submm camera w/ 13’ FoV
- Primary band 350 μm; secondary access to 450, 200 μm bands
- Meandering inductor coupled direct absorption MKID arrays
Long-Wavelength Camera

- **PI:** Sunil Golwala
- **Primary Observing Bands**
  - Between 750 $\mu$m and 3.3 mm
  - 6 sub-arrays
  - 20’ FoV
  - $\sim$ 40,000 pixels
- **Technology**
  - Antenna coupled MKID detectors
  - TES/feed-horn coupled backup

<table>
<thead>
<tr>
<th>$\lambda$ [(\mu\text{m})]</th>
<th>$\nu$ [GHz]</th>
<th>$\Delta\nu$ [GHz]</th>
<th>Per-Pixel Sensitivity [mJy s(^{1/2})]</th>
<th>Number of Pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>400</td>
<td>30</td>
<td>18</td>
<td>16384</td>
</tr>
<tr>
<td>850</td>
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<td>1100</td>
<td>275</td>
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<td>3300</td>
<td>90</td>
<td>35</td>
<td>2.7</td>
<td>1024</td>
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</tbody>
</table>
X-Spec: A Multi-Object Spectrometer for CCAT

• PI: Matt Bradford

• Spectral coverage: 195 GHz – 520 GHz in 2 bands

• Redshifts from CO lines at z ~ 0 to 3, fine-structure lines at z ~ 3 to 10

• Resolving power: 400 – 700

• Simultaneous spectra: Between 20 and 300 beams on the sky likely fixed beam positions for larger formats

• Technology: “on-chip” filter bank architecture with MKID readouts

• Fed with swinging arm twin periscopes
CHAI: CCAT Heterodyne Array Instrument

- PI: Jürgen Stutzki
- Heterodyne, dual frequency array
- Operating bands: 500 GHz (600 μm) and 850 GHz (350 μm)
  - 2’ × 2’, 14” spacing at 600 μm
  - 1’ × 1’, 8” spacing at 370 μm
  - Mid-J CO, $^{13}$CO, and [Cl] F-S lines in Galactic star formation regions and nearby galaxies
  - Comets in the HDO $^{110}$-1$_{01}$ 509 GHz line
- 64 (baseline), 128 (goal) pixels in each band
CCAT Consortium Members

- Cornell University (*)
- California Institute of Technology(*)/Jet Propulsion Laboratory
- University of Colorado(*)
- University of Cologne(*) + University of Bonn
- Canadian consortium(**):
- Associated Universities, Inc.
- U.S. National Science Foundation

(*) Signers of CCAT Consortium Agreement and members of CCAT Corp.
(**) Members of Canada Corp., which is in process of joining CCAT Corp.
Project Timeline

- October 2003: Partnership Workshop in Pasadena
- Feb 2004: MOU signed by Caltech, JPL and Cornell
- 2005: Project Office established
- 2006: Feasibility Study Review
- 2007-2010: Consortium consolidation, design development. Site selection completed
- 2010: First-ranked mid-scale project by Astro2010
- 2010 Nov: $11M donation by F. Young
- 2011 Feb: Jeff Zivick takes over as PM
- 2011 Jun: NSF Award of $4.5M toward CCAT
- 2011 Nov: UKÖln/Bonn awarded $9M by German Foundation for CCAT
- 2011-2013: Detailed Engineering Design (EDP) underway ($12.7M)
- mid-2013
- 2013-2017: Construction and First Light