CCAT-p and CCAT Submillimeter Surveys at the best site in the world!

Mike Fich
University of Waterloo
CCAT: Cerro Chajnantor Atacama Telescope

- 25 meter telescope
- Optimized for 350 microns, but operating to 200 microns
- Wide field of view, JCMT: 8 arcmin FOV with 1 degree as goal
- Flexible instrument suite to allow quick changes to match observing conditions
- Partners are Cornell + German and Canadian Consortia
  – Plus Chile and Tokyo Astrophysical Observatory (TAO)
- BUT on hold until US funding situation improves
- Site at 5600 meter on Cerro Chajnantor
  – Fantastic site - significantly better than the ALMA site
Atmospheric Transmission (observed)

2005 Jan 24
Sairecabur
5500 m
93 μm pwv
Marrone et al.
The CCAT Observatory Board decided (in 2016) to look into the idea of building a smaller telescope on the side of the CCAT site

- enable exciting science that requires a site of this high quality, but can be done with a smaller telescope (???)
- preserve the site for CCAT
- gain experience in building and operating an observatory at such high altitude
- provide our instrument builders with a testbed for new technologies
Key Requirements

- High throughput, flat focal plane
  - Mizuguchi-Dragone design
  - **7.8 degree** Field of View
  - Platform for cameras with > 10^5 pixels
  - half wavefront error (HWFE) eq: < 10.7 μm rms (goal: < 7.1 μm rms)

- Aperture diameter: 6.0 m

- Wavelength: 200 to 3100 μm
On March 7, 2017 the CCAT Observatory Board decided to go ahead with the construction of CCAT-p:

- installation will be complete in early 2021
- Telescope commissioning plus instruments installation and commissioning will take at least a year... science start in late 2022?
- “basic” level of funding available now – enough to build complete observatory but limited shortest wavelength capability and limited power/internet
  - Canadian contribution will fill this funding gap
- CLOSE COORDINATION WITH SIMONS OBSERVATORY
CCAT-p Science

Key Projects:

• Galactic Ecology. (Juergen Stutzki)
• CMB and kSZ Galaxy Cluster Survey. (Michael Niemack)
• Intensity Mapping of the Epoch of Reionization via the 158 micron CII Line. (Dominik Riechers)
• Survey of Dusty Galaxies at High Redshift. (Gordon Stacey)

All surveys: “Observatory Projects”, no P.I. Science
Key Projects

- Right now (!) (in weekly telecons) the Key Projects teams are trying to determine what are the optimum instruments for their projects (also currently have software telecons – software lead is Mike Nolta, CITA)
- The teams are open to anyone at any of the participating institutions/consortia
  - Canada is participating through CATC (Canadian Atacama Telescope Consortium, (Incorp. 2012))

Members of CATC are: Calgary, Dalhousie, McGill, McMaster, Toronto, UBC, Waterloo, Western
CATC “Observers” are: Alberta, Lethbridge, Manitoba, Saint Mary’s, and NRC.
"Strawman" Instruments

<table>
<thead>
<tr>
<th>Name</th>
<th>Primary Science</th>
<th>λ range</th>
<th>FoV</th>
<th>No. Pixels</th>
<th>1st Light?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAI</td>
<td>G Eco</td>
<td>200 – 700</td>
<td>17’ x 8.5’</td>
<td>128 (256 goal)</td>
<td>yes</td>
</tr>
<tr>
<td>P-Cam</td>
<td>kSZ</td>
<td>350 – 3100</td>
<td>~3° dia</td>
<td>5.9x10^4</td>
<td>partial</td>
</tr>
<tr>
<td>P-Cam+</td>
<td>IM/EOR</td>
<td>967 – 1620</td>
<td>--</td>
<td>2.0x10^4</td>
<td>no</td>
</tr>
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P-Cam and P-Cam+(FP) we will turn (part of) P-Cam into an imaging Fabry-Perot interferometer. Inserted into the appropriate place in the optical path of one, or several, of the P-Cam sub-camera units.
An excellent detector technology

- McMahon at U. Michigan and NIST have received NASA funding to develop higher frequency polarization-sensitive detectors.
- Multichroic design like is used on ACT, but with 4 bands per feedhorn: 740 um, 860 um, 1.1 mm, 1.3 mm.
- These bands are important for intensity mapping, SZ, polarization, and SMG measurements.
- We are working on microwave SQUID readout appropriate for these arrays.
- 350 um band requires a different technology: MKIDs.

Next steps: Specify and propose for array funding.

Cost effective, low risk technology for CCAT-prime first light science.

Second Generation Instrument

CMB Stage IV
- $10^5 - 10^6$ pixels
- Use the full 7.8° FOV
- Wavelengths from 350μ to 3100μ
- In collaboration with Simons Observatory
Canadian Participation

• Science cases (Bond, Scott, Plume, Rosolowsky, Johnstone, Chapman, ...)
• Facility/telescope
  – Software (Nolta)
  – Optics alignment (Naylor, Fich)
• Instruments
  – CHAI (Plume)
  – Readouts (Halpern)
  – Mechanisms, optics, ? (Chapman)
  – Software
  – Opportunity to build optics tubes
    • e.g. $10^5$ pixels @200 micron with resolution of 8 arcsec
CCAT Observatory

• A fantastic site (in Chile, Atacama region) for submillimeter observing
• Long Term Goal: 25 meter CCAT optimized for wide-field observing at 350 microns
• Short Term Goal (and currently underway): a “pathfinder” for CCAT.
  – CCAT-prime (CCAT-p) will be a 6 meter extremely wide field (almost 8 degrees!) with instrumentation for wavelengths of 200 micron to 3 millimeter
Water Vapour

- The Earth’s atmosphere blocks most wavelengths of light... in the FIR and submillimeter the main culprit is water vapour.
- Measured as Precipitable Water Vapour (PWV) and typically several to tens of millimeters
- Water vapour both blocks emission from space and contributes to the brightness of the sky
  - The effect of water vapour is exponential on cutting the transmission
sub-mm at 4000m altitude (Mauna Kea)

Mauna Kea median PMV = 1.6 - 2 mm
Atmospheric Transmission of Light

Mauna Kea

Transmission

0 0.5 1

log (wavelength (meters))

-12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3

Sea level

Good

bad

gamma rays
X-rays
ultraviolet
visible
infrared
millimeter/sub-millimeter
radio

17/09/13
Future of Canadian Radio Astronomy (Fich)
median=1.0 mm

APEX
(beside ALMA, at 5000 meters)
• Inversion layer traps moisture – up to 90%
• Water vapour is the main barrier to observations at these wavelengths
• Inversion layer drops at night
Inversion Altitude Lower at Night (Atacama measurements)
Atmospheric Transmission (model)

1 mm = 300 μm
The CCAT-p Concept

**GEco: Galactic Ecology of the dynamic ISM**

- Spectral (+continuum) mapping of fine structure and mid-/high-excitation CO lines as diagnostics of physical conditions and motions
  - Lines trace coolants in regions of molecular cloud/star formation in range of SF environments
  - High site essential for shortest submm λs/THz
  - Maps at (15” × λ/350μm) resolution over degree scales of MW including GC plus MCs (low metallicity)
  - Builds on SOFIA (2.5m) with better resolution and much more observing time
  - CHAI under construction (J. Stutzki, U Cologne)
The CCAT-p Concept

**SZE**: Sunyaev-Zel’dovich Effect

Spectral distortions of CMB spectrum:
- **tSZ**: due to random thermal motions of scattering electrons
- **rSZ**: due to populations of relativistic electrons
- **kSZ**: due to bulk velocity of the cluster relative to the CMB rest frame
The CCAT-p Concept

**kSZ**: Kinetic Sunyaev-Zel’dovich Effect

- **tSZ**: dashed red
- **rSZ**: dashed orange
- **kSZ**: dashed blue

- Challenge to characterize and remove CMB, tSZ, bright submm galaxies and radio sources
  - Observations over wider range of $\lambda$s inc. submm
  - Need better sensitivity and resolution than Planck

**Simultaneous bands**

350 $\mu$m – 3 mm
The CCAT-p Concept

**kSZ: Kinetic Sunyaev-Zel’’dovich Effect**

- 3000 hour survey, 1000 sq deg
- dark energy and modified gravity constraints based on measuring 1000 clusters with 100 km/s accuracy (red); SPT-3G projections shown in blue.
- Such uncertainties will also enable a measurement of the sum of neutrino masses with a 1σ uncertainty of ~0.03 eV.
The CCAT-p Concept

**kSZ: Kinetic Sunyaev-Zel’dovich Effect**

A survey of 3000 hours, over ~1000 sqd with CCAT-p will substantially improve on upcoming CMB surveys.

On going analysis by M. Niemack and F. deBernardis

“no gal noise”: sub-mm emission from faint galaxies perfectly subtracted
The CCAT-p Concept

IM/EOR: 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 at z = 6-8 of few arcmin good match for 6-m aperture (1’ @ 1mm) plus mapping speed
  - Need moderate spectral resolution R~300-500
    - Spectral imaging technology will improve with time
  - Instantaneous bandwidth over mm band (1.1-1.4 mm requirement; goal of 0.95-1.6 mm to get z = 5 to 9)
    - Identify interloper lower z CO lines
    - Atmospheric stability of high site advantageous
The CCAT-p Concept

Familiar example of Intensity Mapping
Familiar example of Intensity Mapping

Spectral line intensity mapping:
- Not just fluctuation spectrum but how it changes over EOR redshift interval
The CCAT-p Concept

**IM/EOR: Intensity Mapping of [CII] from the EOR**

- Detect aggregate clustering signal of faint galaxies in the EOR via redshifted [CII] 158 μm line
- [CII] directly traces sources of reionization (SF galaxies)
  - Recent ALMA detection of [CII] in “normal” galaxies at z = 5-6 (e.g. Riechers+ 2014)
  - Enhanced [CII] to dust continuum compared to lower redshifts → strong signal
The CCAT-p Concept

Full power in combination with HI 21cm experiments
- HI 21cm: traces neutral gas not yet re-ionized
- [CII] 158\textmu m: traces ionization sources (star forming galaxies)
The CCAT-p Concept

Full power in combination with HI 21cm experiments
- HI 21cm: traces neutral gas not yet re-ionized
- [CII] 158μm: traces ionization sources (star forming galaxies)

[CII] advantage:
- No radio frequency interference
- Can be done before full SKA built
The CCAT-p Concept

**IM/EOR:** Intensity Mapping of [CII] from the Epoch of Reionization

- Detect aggregate clustering signal of faint galaxies in the EOR via redshifted [CII] 158 μm line
- Spectral line IM gives 3-D spatial information
  - Process of structure formation
  - Fluctuations trace DM density fluctuations
- SKA 21 cm HI line (HERA)
  - Requires SKA collecting area
  - Foreground contamination/RFI

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.
The CCAT-p Concept

**CMB: Future Stage IV CMB Observatory**

- Next generation CMB mapping
  - Probe inflationary gravity waves at tensor-to-scalar ratios as low as 0.001
  - High-significance measurement of neutrino mass sum
  - High-throughput, wide-field, flat focal plane design at high site even on modest aperture telescope would enable mapping CMB 10X faster than ACTPol or SPT-3G
- CCAT-p would offer existing platform for deployment of cameras with > 10^5 detectors, likely developed with DOE funding on 5+ year timescale.
Dust reprocesses starlight into FIR

Cosmic expansion shifts light of early galaxies further into submm and mm bands

Lagache, Puget, & Dole 2005
Dust reprocesses starlight into FIR

Cosmic expansion shifts light of early galaxies further into submm and mm bands

Lagache, Puget, & Dole 2005
The CCAT-p Concept

Instrumentation

- **P-Cam**: Modular, wide-field imaging camera for \textit{ksz}
  - Based on design of CCAT SWCam; reconfigurable
  - One module at 350 $\mu$m for first light; others TBD
  - Optimized layout for \textit{ksz}

- **CHAI**: Heterodyne array spectrometer for \textit{Geco}
  - Under construction at UCologne (J. Stutzski)

- **“P-Spec”**: Imaging spectrometer for \textit{IM/EOR}
  - P-Cam(+FP): initial modification of P-Cam as an imaging Fabry-Perot interferometer
  - Future development of grating MOS?

- **“P-CMBcam”**: future CMB camera
Instrumentation Req’s

• Requirements on telescope
  – 1x principle mount: 3 m cube, 5000 kg
  – 1x or more subordinate mounts: 2x2x3 m, 1200 kg
  – Instrument handling (mount/unmount)
  – Active instrument selection (switchover < 10 min.)
  – Electronics & process spaces: 4000 kg, 12 sq m

• Requirements on infrastructure
  – electrical budget ~3/4
  – data rate budget 70-90%
  – cooling budget > 90%
CCAT-prime instrument concept

- Detector wafer layouts
  - Old CCAT-prime calculations assumed one 15cm wafer/tube
  - New “45 cm” optics configuration will fit 3-4 wafers/tube
  - 7 wafer layouts per tube are less practical

Wafer configurations from Simons Observatory Collaboration

1-wafer
\[ d = 130 \text{ mm} \]

2-wafer
\[ d = 275 \text{ mm} \]

3-wafer
\[ d = 282 \text{ mm} \]

4-wafer
\[ d = 363 \text{ mm} \]

25 cm optics tube

"45 cm" optics tube

https://docs.google.com/spreadsheets/d/1jsDegB6ehDu92HSQdOfrFl2-4aDLbHg7pNYKPKvwV/edit?usp=sharing
CCAT-prime instrument concept

- Larger/higher throughput version of SWCam
  - 7 optics tubes that can each illuminate 3-4 detector wafers
    ⇒ Up to 21-28 wafers when fully populated (note: 3 wafers are on ACT now)
  - Similar to Simons Observatory (SO) optics tube designs
  - Initially propose 3 to 5 tubes with 9 to 15 wafers
    - Intensity mapping spectrometer in 1 or 2 tubes with 2 to 6 wafers
    - Cluster 4 band polarimeters (0.75, 0.86, 1.1, 1.3 mm) in 1 or 2 tubes with 3 to 6 wafers
    - 350 um band (DSFGs and clusters) in 1 tube with 3 wafers
  - Upgradeable with more tubes and/or arrays later

SO sketch: telescope + 13 tubes from P. Mauskopf
Instrument space
Initial Summit Concept
Assumptions

- 15 year lifetime
- 24-hr duty cycle (conditions permitting)
- Remote observing from San Pedro
- Campaign mode operations
- Min. high site maintenance (goal: 1 / wk)
- Capacity for 2-3 science instruments
- Access road constructed by TAO
- Connection to ALMA infrastructure for electrical power and data transfer desired
Environment

- Operating: (measured 2006 – 2012 at 5600 m site)
  - Air temperature = -21 to +9 C
  - Air pressure = 50 to 53 kPa
  - Wind speed < 9 m/s peak
  - Solar radiation (i.e. daytime ops, but not on mirrors)

- Survival:
  - Air temperature = -30 to +25 C
  - Wind < 69 m/s (270-yr return wind, 5% prob.)
  - Rain / ice / snow / seismic event
  - Utility power failure
Support Infrastructure

- Access Road
- Power Generation and Supporting Connections
- Command, Control and Data Handling Systems
- Main Operations Center (San Pedro de Atacama)
- Summit Operations & Other Structures (Containers)
- Timing System
- Cooling Plant
- Weather station and Water Vapor Radiometer
- Wavefront Sensor and Optical Pointing Telescope
- Alignment Systems (Towers, Targets, etc.)
CCAT: a large single dish submm telescope at an excellent site

- Strong science case
  - Highly ranked in both Canadian and US decadal plans
- Many partners (in Canada, US, Germany, Chile) plus many others interested in joining
  - Canadian involvement since late 2005
- BUT, as is the norm in big instrument projects, this project has faced numerous delays
- Currently the CCAT team is working on CCAT-p as a forerunner to CCAT
CCAT: Broad Range of Scientific Goals

- The resolution of the CFIRB into individual sources at 350 μm, and the accurate characterization of the global star formation history of the Universe, from the era of re-ionization to the present day, and its dependence on environment, halo mass
- The measurement of the mass function of interstellar cloud cores and its variance with environment and through cosmic time, key to understanding the properties of the stellar IMF
- The formation, evolution and kinematics of galaxy clusters via the Sunyaev-Zel’dovich (SZ) effects
- Cosmology: tests of gravity, dark energy, cosmic flows and redshift distortions, clustering, baryonic acoustic oscillations, esp. in z=3-5 epoch
- Solar System: D/H, TNOs
The CCAT Team in Canada

- Goal: 25% of CCAT (out of ~$160M(US) )
  - Members of Canadian Atacama Telescope Consortium (CATC) Inc.
- includes 42 faculty members working in submm astronomy, extensive experience with the JCMT, SPT, ACT, various balloon experiments, Herschel, Planck