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THE CERRO CHAJNANTOR ATACAMA TELESCOPE (CCAT)

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Subject headings:

1. SUMMARY

"How did we get from energy fluctuations in the early Universe to galaxies, stars and planets?". This is one of the fundamental problems in astrophysics, and the 25 meter diameter CCAT is a unique project geared towards the investigation of this question. CCAT will have a sensitivity similar to that of ALMA (the Atacama Large Millimeter Array) at submillimeter wavelengths but will be much faster than ALMA when mapping in the continuum. Located on the peak of Cerro Chajnantor close to, but significantly higher, than the ALMA site, will allow CCAT to operate at wavelengths as short as 200 μm, considerably better than the ALMA wavelength limit.

New technologies are allowing us to build submillimeter/far infrared cameras of unprecedented size, fully populating the focal plane of the telescope. CCAT will have a large enough field of view to accommodate a detector 20 arcminutes in diameter and populated with greater than 100 kilopixels. When this larger and even more sensitive camera is combined with the excellent site, CCAT will map the sky 1000 times faster and with better resolution than SCUBA-2, the current state-of-the-art detector. CCAT will also be equipped with a variety of other instruments including spectrometers such as broad-band direct-detection grating instruments (such as the existing ZEUS and Z-spec at the CSO), heterodyne focal plane arrays (such as HARP at the JCMT), and Fourier Transform Spectrometers.

CCAT is currently a joint project between Cornell University, the California Institute of Technology, Jet Propulsion Laboratory, the University of Colorado, a rapidly growing consortium of Canadian universities, the United Kingdom Science and Technology Facilities Council (STFC), and the Universities of Bonn & Köln.

CCAT will arrive at a time when ALMA will have been in use for at least five years and no other comparable submm facility is likely to exist (with both JCMT and Herschel having reached the end of their operations at least four years before CCAT can begin operations). Canadian contributions to CCAT will likely include the observatory dome, parts of the continuum cameras, heterodyne focal plane arrays, FTS, polarimeter, and software for both data analysis and for the data archive. Thus, CCAT will continue the legacy of the JCMT and guarantee that a strong Canadian academic tradition continues to flourish in the increasingly important area of submm science, training, and instrumentation.

2. KEY SCIENCE GOALS

In this Section, due to space restrictions we briefly discuss a only few of the science paths CCAT will tread. Broader and more detailed descriptions can be found in Science White Papers by Scott *et al.*, Matthews *et al.*,Johnstone *et al.*, and Barmby *et al.*.

2.1. *Measuring the Star Formation History of Galaxies Across Cosmic Time*

A comprehensive picture of galaxy formation and evolution must account for the bolometric luminosities of galaxies across cosmic time. COBE revealed a cosmic far-infrared (FIR) extragalactic background radiation with flux approximately equal to the integrated extragalactic optical and ultraviolet starlight in the Universe. The most luminous star forming galaxies emit the bulk of their light in the FIR/submm and most of the light from high z galaxies reaches us in that spectral domain. Submm spectral probes are keenly sensitive to physical conditions of the gas, thereby elucidating the context for star formation and providing a crucial observational link between the buildup of the stellar masses and central supermassive black holes.

To determine the amount of energy that has been released by galaxies, it is essential to measure their rest-frame FIR radiation, which peaks at 50 - 200 μm and is redshifted into the submm bands for $z > 1$. Dust emission comprises 50% of the total integrated luminosity of galaxies. That fraction is even larger for the most luminous galaxies and galaxies at high z. The amount of FIR/submm emission – and thus of star formation – from dusty galaxies is impossible to infer from the spectral properties of the escaping optical/UV light alone. Submm observations have a strong advantage in searches for high redshift galaxies: the negative K-correction. Because the slope of the product of the Planck function and the emissivity function of dust grains varies steeply with frequency on the Rayleigh-Jeans side of the spectrum ($S_\nu \propto \nu^{3-4}$), the observed brightness of a galaxy is independent of z from $1 < z < 10$, in that spectral regime. Thus submm surveys provide a natural means for identifying high-redshift ($z > 5$) galaxy candidates within large-scale surveys: those with weak 200 - 700 μm emission and bright 800 μm to mm–wave emission.

SCUBA-2 on the JCMT and the *Herschel Space Observatory* will have an important impact in this field in the next few years. However the confusion limit for CCAT will be significantly better than for either of these telescopes allowing CCAT to reach substantially further down the luminosity function. The greatest gain for

CCAT over SCUBA-2 may be due to its smaller beam at 200 and 350 μm then SCUBA-2 achieves at 450 μm. The CCAT resolution will be good enough that reliable matches to optical and near-IR surveys will be possible, something that has proven very difficult at the resolution that the JCMT provides.

Furthermore, *Herschel's* cryogen will be exhausted approximately when ALMA comes on line, precluding any opportunities for coordinated observations or surveys. On CCAT, a 10 square-degree survey – covering a cosmologically relevant volume – could be covered to a depth of 0.2 mJy rms at 350 μm in 2,000 hours, yielding of order 10^5 mostly faint, distant galaxies. Moreover, CCAT will carry out a spectroscopic survey of submm galaxies, using multi–object versions of broadband direct-detection grating spectrometers such as Z–Spec and ZEUS, now in use at the CSO.

2.2. *Star Formation and the ISM in Nearby Galaxies*

To understand the strong evolution of star formation over cosmic time, nearby, spatially resolved galaxies must be studied to relate the astrophysical probes to high z systems: resolved submm images will reveal the interplay between the star formation process and the natal interstellar medium (ISM). Of particular interest are the most active regions in nearby normal and starburst galaxies; these regions will provide the best templates for the distant, LIRG and ULIRG-class galaxies responsible for the bulk of the cosmic FIR background.

Multi-wavelength studies in concert with submm observations will address fundamental questions about star formation in galaxies, such as: What are the relationships between the age (chemical abundances) of the ISM, the degree of star formation activity, galactic morphology, and the environment? What triggers galaxy-wide starbursts? Do starbursts end by consuming all the available fuel or by disrupting the natal environment through stellar winds?

Multi-band images can trace the process of gas compression in spiral density waves, the formation of stars in molecular cloud cores, and the disruption of the parent clouds by newly formed stars. The FIR/submm spectral regime provides a wide variety of extinction-free spectral–line probes of both ambient radiation fields and the physical properties of interstellar gas (e.g., density, temperature, dynamics, radiation intensity and hardness). Most of those lines lie within a few hundred K of the ground state and have modest critical densities; the emitted radiation is nearly always optically thin. They are important (often dominant) coolants for the phases of the ISM relevant to star formation processes.

The most important FIR and submm lines include fine-structure lines from abundant species (C, CII, NII, NIII, OI, OIII), plus the J = 4–3 to 13–12 rotational transitions of CO. These lines are very bright in star forming galaxies, often summing to more than 1% of the total galaxy luminosity. With Fabry-Perot, Fourier transform, or waveguide–fed multi-object spectrometers, CCAT will be able to deliver spectroscopic images of nearby galaxies in the [NII] 205 μm, [CI] 370 and 609 μm, mid–J CO (e.g. 4–3, 6–5, 7–6) and ^{13}CO(6–5 and 8–7) rotational lines at angular resolutions as fine as $2''$. In the nuclei of some galaxies (e.g. ULIRGs), it would detect CO emission up to J = 13-12 (200 μm) arising from nuclear clouds highly excited by starbursts, or even CO emission from AGN-excited molecular tori, thus providing a link between stellar mass buildup and supermassive black hole growth.

2.3. *The Origin of the Stellar IMF*

In the Milky Way, it is often claimed that the stellar Initial Mass Function (IMF) is remarkably consistent across a variety of environments. The origin of this uniformity, if true, is unknown. Among the physical processes that may lead to a seemingly invariant IMF are gravitational or turbulent fragmentation, feedback from stellar winds and outflows, competitive accretion, ejection of protostellar cores and stellar mergers.

An intriguing possibility is that the mass function of dense clumps in molecular clouds, identified by their thermal dust emission, has a similar shape to the stellar IMF, suggesting that the clump mass function translates into the stellar IMF. CCAT observations will establish if the clump mass function follows the stellar IMF to the substellar (brown dwarf) regime, and if the clump mass function is similar over a wide range of environments in the Galaxy. If the clump mass function is invariant, it will provide compelling evidence that the stellar IMF is imprinted in the fragmentation structure of molecular clouds.

Existing measures of the clump mass function are very heterogeneous and therefore hard to intercompare. CCAT will be able to measure the mass function better than any other instrument including the largest scales, difficult for an interferometer such as ALMA, and done to substellar scales where the resolution of existing single-dish instruments is not good enough. Sensitivity, resolution, mapping speed and λ–coverage of CCAT will uniquely enable Galactic surveys that can link the stellar IMF to the physics and topology of the ISM.

2.4. *The Sizes of Trans–Neptunian Objects*

In recent years, several hundred Solar System objects beyond Neptune have been discovered (TNOs). They are believed to have formed in the outer reaches of the protoplanetary disk around the Sun and to have undergone very little evolution since their early formation. The primitive nature of the material in this region holds important clues towards our understanding of the formation and evolution of the Solar System. The measurement of TNO sizes is important not only to characterize the population properties but also because a knowledge of the sizes yields albedos and inferences on their surface properties. CCAT will make possible a statistical investigation of both the size distribution and surface properties of TNOs. No other instrument or telescope currently under development or planned will rival CCAT's ability to find these objects.

3. TECHNICAL OVERVIEW

3.1. *The Facility*

The CCAT science case, observatory requirements, and conceptual design were developed as part of a $2M study jointly funded by Cornell and Caltech/JPL, which resulted in a Feasibility/Concept Design Study Report[1].

[1] *http://www.submm.org/doc/2006-01-ccat-feasibility.pdf*. See also Section 4.

The overall specifications for the CCAT observatory are listed in Table 1. These specifications were derived by considering a broad spectrum of science programs ranging from studies of Trans-Neptunian objects to surveys for high z submm galaxies. Commonly recurring themes include the need for high sensitivity approaching that of ALMA, excellent angular resolution to enable target identification and overcome spatial confusion, and a wide wavelength coverage in order to constrain the spectra and luminosities of dusty objects. These considerations led to the choice of a 25 m telescope with a 20' field of view, a half-wavefront error (HWFE) around $10\,\mu$m rms for high aperture efficiency at 350 μm, and a location on a high (5600 m) mountain site in Atacama above the ALMA plateau for routine access to the 350 μm atmospheric window.

Consistently superb observing conditions are crucial for achieving CCAT's scientific objectives. For observations at submm wavelengths, a site with very little atmospheric water vapor is paramount. The proposed site for CCAT is at an altitude of 5612 m, on a plateau about 50 m below and 200 m east-north-east of the summit of Cerro Chajnantor (Figure 1), within the Science Preserve established by the Chilean Government. At 600 m above the ALMA site the CCAT site offers nearly twice as much high-quality observing time in the crucial $350/450\,\mu$m atmospheric windows.

Multiple factors – the 25 m aperture, the improved atmospheric transparency of the higher site, the use of broadband continuum detectors the high aperture efficiency resulting from $\sim 10\,\mu$m rms optics and the possibility of achieving sensitivities limited by photon statistics and not by receiver noise – combine to give CCAT a continuum point-source flux sensitivity in the 350 μm and 450 μm atmospheric windows that is comparable to ALMA on a per-pixel basis. (Figure 2 compares the expected CCAT sensitivity to other instruments.) Therefore, with the use of large array cameras, the mapping speed for CCAT will be many orders of magnitude faster than ALMA (potentially 10^5 for the 100 kilopixel camera) enabling large–scale surveys and providing extraordinary complementarity with ALMA.

The optical design of CCAT foresees a compact Ritchey–Chrétien with f/0.4 hyperboloid PM, which allows for a relatively compact Callotte-type 40 m dome. as shown in Figure 3. **This particular design has been studied in considerable detail by Canadian industry and it is likely that this will be the largest part of the Canadian contribution to CCAT.**

3.2. *The Instruments*

The scientific power of CCAT derives from recent advances in submm detector array technology. Array sizes have been growing exponentially. At present, the state of the art is represented by the kilopixel-scale arrays of superconducting transition-edge sensor (TES) bolometers now in use at SPT, ACT and in the SCUBA 2 instrument at the JCMT. For CCAT, the goal is to have cameras with up to $\sim$ 50 kilopixels available at "first light"[2]. Two cameras are envisioned: one at short wavelengths, $200-620\,\mu$m, and one at long wavelengths, covering $740-2000\,\mu$m. With 50,000 Nyquist-sampled pixels, CCAT's field of view could be filled at $\lambda = 1\,$mm. However, since the number of pixels required scales as λ^{-2}, filling the field of view at 350 μm would require of order 400 kilopixels. Clearly, building instruments at this scale presents a broad spectrum of technical challenges including cryogenics, optics, baffling, shielding, electronics, and mechanical issues. These are long-term challenges: it is important to remember that CCAT can produce outstanding science even with existing kilopixel-scale arrays.

Similar challenges exist for spectroscopic instrumentation A CCAT goal is to construct broadband direct-detection grating spectrometers, capable of determining z via the [CII] or CO lines. Existing examples include the ZEUS and Z-spec instruments now in use at the CSO. However, CCAT will go beyond these single-beam instruments and host multi-object spectrometers capable of observing 10–100 objects simultaneously while spanning multiple atmospheric windows. Again, this presents numerous technical challenges. It is now also possible to construct large heterodyne array instruments for high-resolution spectral mapping. The 64-pixel 350 GHz system in construction at U. of Arizona provides one example; ultimately, heterodyne systems with 256–1024 pixels should be possible.

4. MANAGEMENT STATUS

The CCAT partnership was initiated in 2004 through an MOU signed by Cornell University and the California Institute of Technology. The consortium was joined in 2007 by the University of Colorado, a consortium of Canadian universities and the United Kingdom ATC. and then in 2009 by a consortium of German Universities and by Associated Universities, Inc. of Washington, D.C.

CCAT will take six years to complete from the date when sufficient funding is in hand. Planning has continued to improve as the design has matured and additional site information has become available. The current estimates of cost for the telescope and associated facilities are based on the analysis carried out in the course of the Feasibility Study of 2004–2006. The US CCAT partners anticipate requesting funds for operations and surveys from the NSF. Caltech would close the CSO, presently supported by the NSF, in preference for CCAT.

The minimum "buy-in" to be a major partner in CCAT is to contribute a 20% share of the costs: $22M (US) plus operating costs for a minimum of five years. In addition to the dome, Canada will also contribute to instruments with contributions very similar to, but a generation more sophisticated than, those built in Canada for the JCMT. These may include parts of the continuum cameras, polarimeters, and imaging Fourier Transform Spectrometers and software both for data analysis and archives. A potential major all-Canadian contribution is large heterodyne focal plane arrays (see the white paper by S. Claude!) and the correlator back-ends. All of the proposed Canadian contributions are in areas in which there is a significant heritage and expertise within Canada, and indeed CCAT will help to ensure that the there is an even higher return for the investments already made in these areas. similar to, but a next-generation more sophisticated than, those built in Canada for the JCMT.

TABLE 1
CCAT SPECIFICATIONS

Specification	Requirement	Goal	Remarks
Aperture	25 m		sensitivity, confusion
Wavelength range	$350 - 1400\,\mu$m	$200 - 3500\ \mu$m	dust SED
Field of view	$10'$	$20'$	large-format arrays
Angular resolution	$3''.5$–$14''$	$2''$–$35''$	$\theta = 1'' \times \lambda/(100\,\mu\text{m})$
Half Wavefront Error	$< 12.5\ \mu$m	$< 9.5\ \mu$m	rms (HWFE)
Site conditions	< 1 mm	< 0.7 mm	median pwv
Polarization	0.2%	0.05%	after calibration
Emissivity	$< 10\%$, $\lambda > 300\ \mu$m	$< 5\%$, $\lambda > 800\,\mu$m	sky loading is low
	$< 20\%$, $\lambda = 200\ \mu$m		
Elevation range	$5 - 90°$		from horizon
Azimuth range	$\pm 270°$		from north
Pointing, blind	$2''$	$0''.5$	rms
offset	$0''.3$	$0''.2$	within 1°
repeatability	$0''.3$	$0''.2$	rms, one hour
Scan rate	$0°.2\ \text{s}^{-1}$	$1°\ \text{s}^{-1}$	slow and fast modes
acceleration	$0°.4\ \text{s}^{-2}$	$2°\ \text{s}^{-2}$	efficient scan patterns
pointing knowledge	$0''.2$	$0''.1$	rms
Secondary nutation	$\pm 2'.5$		@ 1Hz, azimuth only

FIG. 1.— *Left:* Cerro Chajnantor as seen from the ALMA plateau. *Right:* A view of the CCAT proposed site.

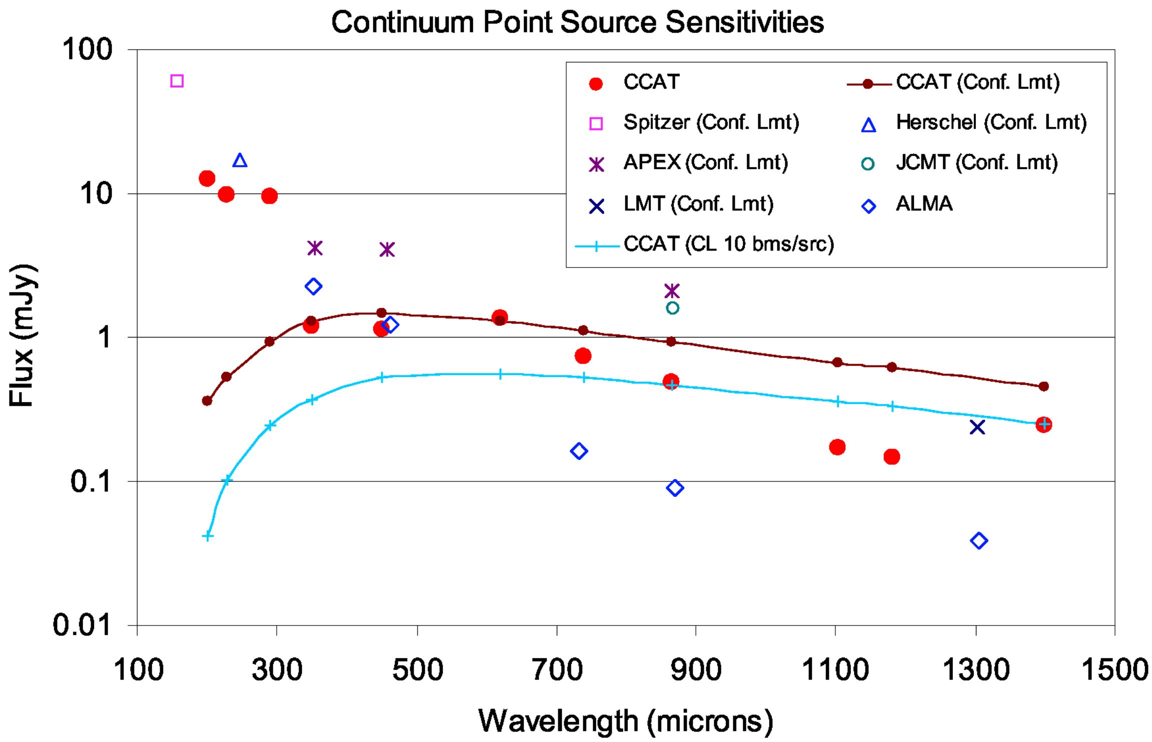

FIG. 2.— CCAT continuum point-source sensitivity per pixel compared to other facilities, calculated for a 5σ detection in one hour integration.

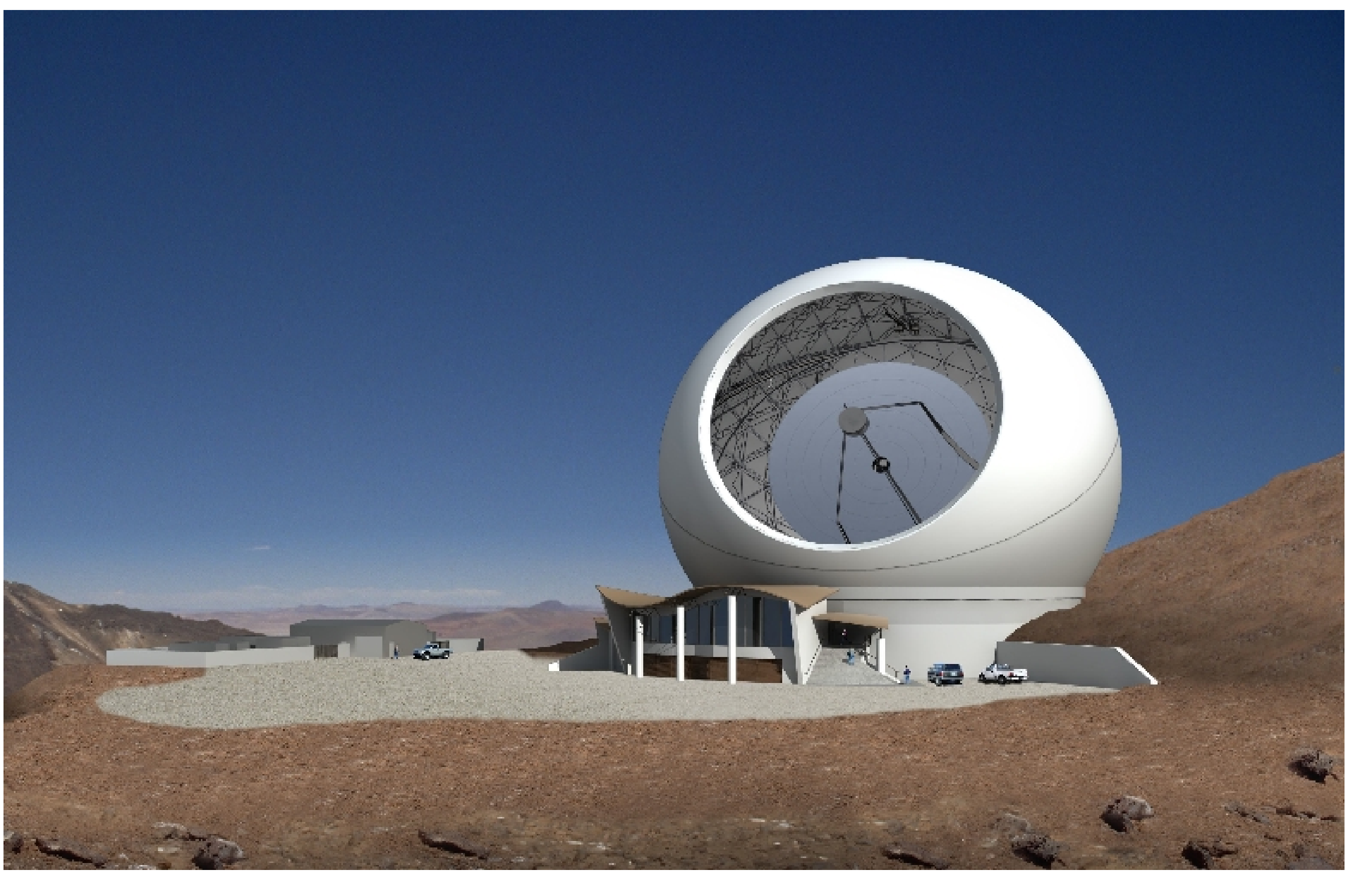

FIG. 3.— An artist's view of CCAT at the proposed site on Cerro Chajnantor