A Cryogenic Telescope for Far-Infrared Astrophysics: A Vision for NASA in the 2020 Decade

C.M. Bradford[1] and others

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see full document at: `http://conference.ipac.caltech.edu/firsurveyor/page/documents`

Abstract

The Far-IR Science Interest Group will meet from 3–5 June 2015[2] with the intention of reaching consensus on the architecture for the Far-IR Surveyor mission. This paper is an except from a larger document which describes one of the architectures to be considered by the community. We present the Cryogenic-Aperture Large Infrared-Submillimeter Telescope Observatory (CALISTO), a 5-meter class, space-borne telescope actively cooled to T$\sim$4 K, emphasizing moderate-resolution spectroscopy in the crucial 35 to 600 μm band. CALISTO will enable NASA and the world to study the rise of heavy elements in the Universe's in the first billion years, chart star formation and black hole growth in dust-obscured galaxies through cosmic time, and conduct a census of forming planetary systems in our region of the Galaxy. CALISTO will capitalize on rapid progress in both format and sensitivity of far-IR detectors. Arrays with a total count of a few $\times 10^5$ detector pixels will form the heart of a suite of moderate-resolution (R$\sim$500–1000) imaging spectrometers in which each detector reaches the photon background limit. Other instruments are also under consideration, including broad-band imagers and high-spectral-resolution (R>10,000) spectrometers.

1 Motivation for Sensitive Wideband Far-IR Spectroscopy

The sensitive CALISTO platform is especially compelling for wideband spectroscopy, as Figure 1 shows and Table 2 presents. CALISTO will obtain full-band spectra of thousands of objects ranging from the first dusty galaxies to the most heavily enshrouded young stars and proto- planetary disks in our own Galaxy, as well as blind discovery of thousands more. These CALISTO spectra will directly address several key goals of modern astrophysics:

- Measure the onset of heavy elements and the rise of organic molecules in the Reionization Epoch. See white papers by Cooray et al., and Appleton et al. for more information.
- Chart the true history of cosmic star formation and its connection to supermassive black hole growth. More information can be found in a white paper by Armus et al.
- Measure clustering and total emission of faint galaxies below the individual detection threshold using tomographic intensity mapping of the far-IR emission lines.
- Probe the cycling of matter and energy in the Milky Way and nearby galaxies.
- Conduct a census of gas mass and conditions in protoplanetary disks throughout their evolutionary sequence. A white paper by Bergin et al. describes this more fully.

2 Architecture Choice

The scientific goals outlined above require excellent spectroscopic sensitivity, both for point sources and mapping, with full coverage between the 28 μm cutoff of JWST MIRI and the onset of the ground-based windows at $\sim$600 μm. Accessing the earliest galaxies and most-evolved lowest-mass protoplanetary systems requires a line sensitivity below $10^{-20}\,\mathrm{W\,m^{-2}}$, large instantaneous bandwidth, and moderate spectral resolving power ($R = \delta\lambda/\lambda \geq 500$). The requirement for ultimate sensitivity demands maximum collecting area, low telescope background, and high efficiency. Blind spectroscopic surveys over large fields will also be a part of the program, so the observatory must have enough throughput (AΩ) to make use the large-format array technology now available. These crucial attributes are summarized in Table 1. Collecting area per unit cost is maximized with a monolithic-aperture telescope, particularly since the entire telescope and instruments will be actively cooled.

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[1] JPL and Caltech, `bradford@caltech.edu`

[2] `http://conference.ipac.caltech.edu/firsurveyor/`

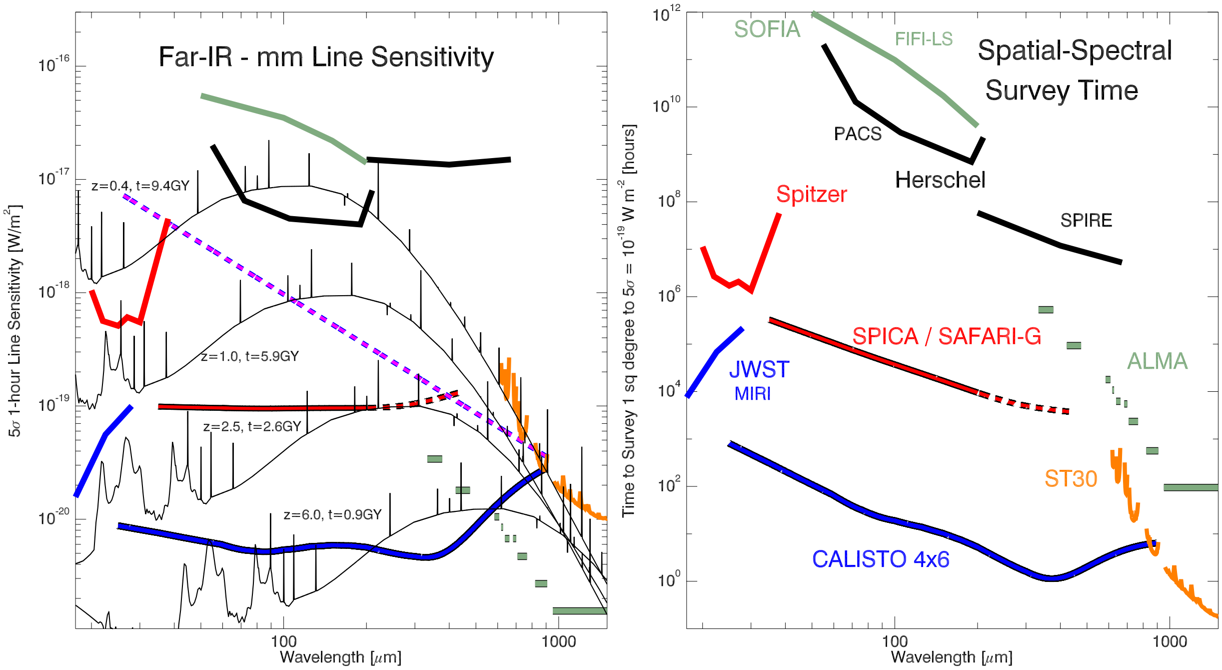

Figure 1: Spectroscopic sensitivities in the far-IR and submillimeter. Left shows the sensitivity in $\mathrm{W\,m^{-2}}$ for a single pointed observation. Galaxy spectra assuming $\mathrm{L} = 10^{12}\,\mathrm{L}_\odot$ at various redshifts are overplotted using light curves, with continuum smoothed to R=500. The magenta dashed line shows the sensitivity of a quantum-limited heterodyne receiver ($\mathrm{T_{sys}}$=hν/k) in a bandwidth of 10 km/s. The right panel shows the speed for a blind spatial-spectral survey reaching a depth of $10^{-19}\,\mathrm{W\,m^{-2}}$ over a square degree, including the number of spatial beams and the instantaneous bandwidth. For more information see the full document.

Cooling all parts of the telescope and instrument environment to a few degrees K is essential for the excellent sensitivity, and this is a firm requirement for CALISTO. Cooling will be provided by closed-cycle helium coolers, carefully integrated into a passive cooling architecture which uses staged V-groove radiators. 4-K class spaceflight coolers have been developed by industries worldwide, and the effectiveness of the V-groove system has been demonstrated with the ESA Planck telescope, which reached below 40 K on orbit.

The telescope design is a topic for study. An example configuration for the telescope is our point design described in Goldsmith et al., 2008 [**?**], and shown in Figure 2. This design features a 4×6-meter monolithic primary mirror used off-axis, and a secondary mirror which is deployed with a single hinge mechanism. This provides an optimal collecting area in a non-deployed primary mirror which fits into a 5-m fairing. While other materials could be considered, a promising approach is to use silicon carbide (SiC), which is attractive given its favorable thermomechanical properties, and given it's success in the Herschel observatory, a system with comparable size and surface accuracy requirements to CALISTO. Other aspects are less clear, and there are several inter-related design choices that we propose to consider in a study prior to the Astro2020 submission including: on-axis vs. off axis, segmented vs. monolithic primary, active (correctable on orbit) vs passive primary, and cost scaling with the primary mirror size.

The approaches for the grating-type spectrometers and the large arrays of frequency-domain-multiplexed supercon-

Table 1: CALISTO Basic Parameters

Parameter	Value
Telescope Temperature	<4 K
Telescope Diameter	∼5 m
Telescope Surface Accuracy	1 μm
Telescope Field of View	1 deg at 500 μm
Instrument Temperature	50–100 mK
Total Number of Detectors	$1\text{–}5\times10^5$
Heat Lift at 4 K	∼150 mW
Heat Lift at 20 K	∼2 W
Data Rate	∼ 1 Gbit / sec

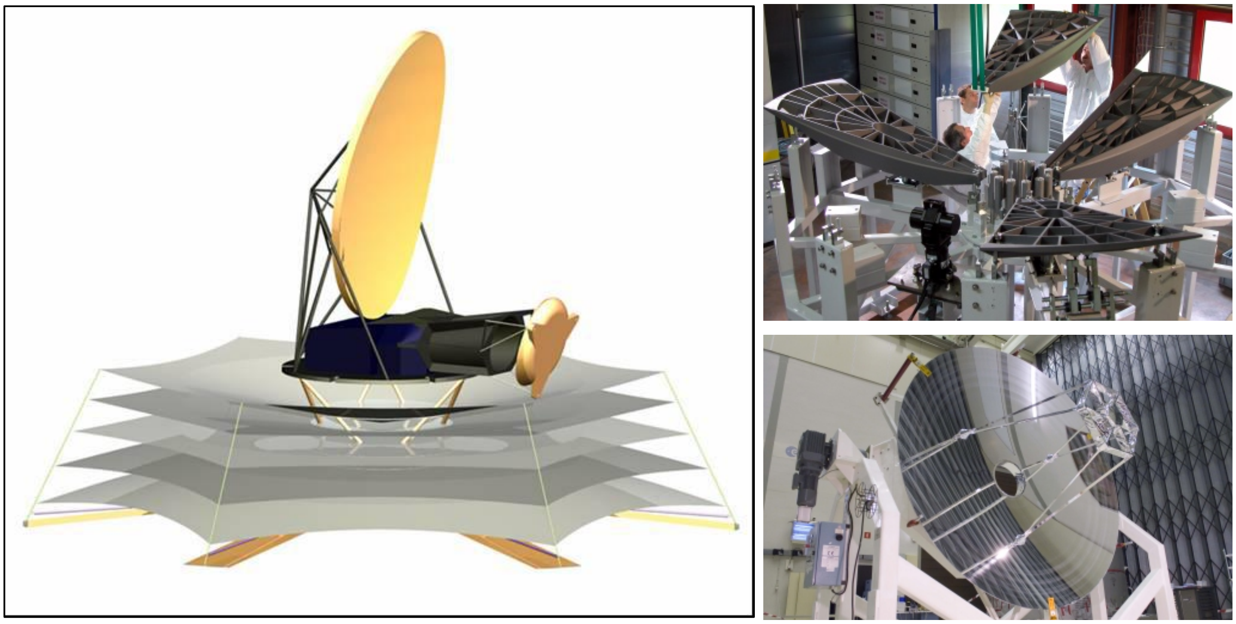

Figure 2: Left: CALISTO concept. 5-meter class telescope is actively cooled with closed-cycle coolers to ∼4 K. Passive and active cooling are integrated in a design which features V-groove radiators as used on Planck and JWST. Right: Large cold telescope heritage: the 3.5-meter Herschel silicon carbide primary mirror, prior to assembly from 8 petals and figuring, and as integrated into the telescope. Other mirror approaches will also be considered.

ducting direct detector arrays are described in the main document. The envisioned capabilities are shown in Figure 1 and Table 2. In addition, we emphasize that a single-dish telescope also naturally accommodates a wide range of other potential instrumentation, for example broadband imaging arrays, heterodyne receiver arrays, and 2-D imaging spectrometers such as Fabry-Perot interferometers. In particular, broadband imaging at 100 μm will be particularly powerful with CALISTO (see white paper by Caitlin Casey), and a modest 4000-pixel camera can yield an all sky survey with an angular resolution of $5''$.

3 Cost Landscape

CALISTO was studied by JPL Team-X in various exercises between 2005 to 2008. The telescope configuration described above, the associated cryocoolers, the deployed sunshade, an allocation for instruments, and operations for a 5-years mission were estimated to cost \$1.7 billion (FY2008\$). Re-assessing this is an important aspect of our proposed pre-decadal study. One key point is that we are now advocating substantially more capable instrumentation for CALISTO. While the new frequency-domain multiplexing schemes naturally enable the large formats, we nevertheless expect that the increased scope will increase both the instrument and science terms in the budget (over the full mission life) relative to the 2008 estimate. On the other hand, much of the science can be retained with a reduction in aperture, so that is a means to reduce cost.

Table 2: CALISTO Spectrometer Backends: R=500 Strawman Design

Parameter	40 μm	120 μm	400 μm	Scaling w/ $D_{\rm eff}$
Dominant background	zodi dust	zodi. + gal. dust	tel. + CMB	...
Photon-noise limited NEP [$\rm W\,Hz^{-1/2}$]	3e-20	3e-20	4e-20	...
Beam size	$1.9''$	$5.9''$	$19''$	$\propto D^{-1}$
Instantaneous FOV [sq deg]	4.0e-5	3.8e-4	2.3e-3	$\propto D^{-2}$
Line sensitivity $\rm W\,m^{-2}$, 5σ, 1h	4.2e-21	3.3e-21	3.2e-21	$\propto D^{-2}$
Pt. sce. mapping speed [$\rm deg^2/(10^{-19}W\,m^{-2})^2/sec$]	1.6e-4	2.4e-3	1.6e-2	$\propto D^2$
Surface bright. sens. per pix [MJy/sr $\sqrt{\rm sec}$]	4.2	1.1	0.33	$\propto D^0$

Notes: Sensitivities assume single-polarization instruments with a product of cold transmission and detector efficiency of 0.25 in a single polarization, and an aperture efficiency of 0.75. FOV estimate assume slit widths of 165 λ/D for the 40 and 120 μm examples, and 100 individual single-beam spectrometer backends for the 400 μm case.