Cryogenic Detectors for Infrared Astronomy: the Single Aperture Far-Infrared (SAFIR) Observatory

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Context

- SAFIR was recommended as a major NASA mission (with JWST, Con-X, TPF) by the NAS Decadal Review
- Recommended for technology and concept development during this decade, for launch late next decade.
- Recognized that large aperture, low temperature Far-IR telescope is now achievable, especially with technology advances from JWST.
- Recognized SAFIR as a scientific successor to SIRTF and Herschel, and as a powerful scientific partner to JWST and ALMA
What is SAFIR?

- SAFIR is a large (~10m), cryogenically-cooled observatory for the far-infrared (20-800µm)

- SAFIR can address several fundamental astrophysical problems:
  - Formation of stars and planets in our own neighborhood
  - Coalescence of galaxies in the early universe

- SAFIR is envisioned as a follow-on to JWST, but extended to longer wavelengths.
Current Status


• GSFC developed SAFIR mission concept, based on JWST, in 2002.

• Funding opportunities for mission concept studies, detector development currently available.
Motivation

- Half the luminosity in the Universe is in far-IR! The young universe is redshifted there.
- Of the far-IR background, $<1/3$ is accounted for by discrete galaxies.
- Star formation – present and distant past – is an IR problem.
- The youngest primordial gas clouds will be visible only in the far-IR.
- Dust is everywhere (eventually) – and obscures understanding

- \textit{Era of JWST and ALMA.}
- \textit{SIRTF, SPICA, Herschel are done.}
SAFIR Science Drivers

- Resolve the FIR background -- trace star formation to $z>5$ in an unbiased way, measuring redshifts directly.

- Understand how primordial material forms stars. Proto-bulges and -disk formation in pristine gas. $\text{H}_2$ @ $z=20$?

- Understand role of AGN in galaxy formation, and relevance to ULIRGS. Unification?

- Bridge gap between local high mass star formation and starburst galaxies.

- Track pre-biotic molecules from cores to planets.

- Identify voids in debris disks around stars.
SAFIR: Molecules to Stars to Planets

SAFIR is a chemistry probe of the warm cosmos

ρ and T structure of collapsing cores, chemical composition, ionization, turbulence, fractionation, synthesis, condensation, disk energetics, B fields

the stuff of protostars, proto-solar systems, debris clouds, comets, planets and the raw material of life

H₂, C, N, O, MgH, H₂O, CHₙ, SiH, SH, HD, LiH, AlH etc. etc. large pre-biotic molecules
SAFIR: Relationship of AGNs & ULIRGs

- $10^{12} \, L_\odot$ galaxies are numerous in early universe; huge $A_v$: Are they super starbursts? Buried AGNs? Some intermediate stage?

- Powerful, extinction-free mid-IR radiation diagnostic lines

- SAFIR can search for broad lines; analyze dynamics of nuclear toroids; accretion history of universe (with X-ray missions)
SAFIR: Comparison of Capability

SAFIR will offer orders of magnitude improvement in:

- point source detectivity (1s of SAFIR worth 1 week of SIRTF!)

- spectroscopic sensitivity (1s of SAFIR worth 1 year of Herschel with noise-free detectors, 1 day with quantum-limited detectors)

no confusion limits for spectroscopy!
SAFIR Mission Implementations

- SAFIR is defined as a set of science objectives that answer key astrophysics questions in the far-infrared.

- Mission architecture is being refined; can be optimized for several different science requirements & technological capabilities.

- All implementations have numerous common technology needs, including detectors.
Technology Challenges

• **Detectors with sufficient sensitivity, in large format arrays.**
• Cooling a large telescope to 4K (& detectors to ~0.05K).
• Deployable cryogenic telescope of 10m class.
• Adequate testing facilities for components & integrated systems.

• **Mitigating factors:**
  – Cryocoolers for ~4K are under development for, e.g., JWST, TPF, etc.
  – Detectors - superconducting TES bolometer development for Con-X
  – Deployable telescope to be demonstrated by JWST
But Why 4K for SAFIR?

Because it makes a big difference!

A 4K telescope is background-limited (zodi @ <200µm, CMB @ >200µm)

At these wavelengths, point source sensitivity is more dependent on temperature than on aperture!
Critical Detector Technologies

- Large-format ($10^3$-$10^4$ pixel) broadband arrays:
  - semiconducting and superconducting (TES) bolometers
  - Ge, Si BiB photoconductors

- Arrays for spectroscopy:
  - RF-SET / STJ
  - Kinetic Inductance

- High resolution spectroscopy:
  - quantum noise-limited heterodyne spectrometers
  - new spectrometer architectures

- Focal plane cooling technologies for <100mK
  - multistage ADR
  - dilution refrigerators
Representative Detectors

- Photoconductors
- Bolometers
- Other
SAFIR Detectors (low resolution)

Camera: 10^4 pixels,
NEP=10^{-19} W/√Hz

LRS: 4·10^3 pixels,
NEP=2·10^{-20} W/√Hz
SAFIR Detectors (med. resolution)

- With $\lambda/\delta\lambda \sim 1000$ (300km/s) resolution, power is low
- Requires $>10^3$ pixels with $\text{NEP} = 3 \cdot 10^{-21}$ W/\sqrt{Hz}
- At 100$\mu$m, rate is $\sim 50 \gamma$/s
- Need noise of $5 \gamma$/s/\sqrt{Hz}
Heterodyne spectrometers are quantum-limited, therefore not optimally sensitive.

Direct detection approach probably not feasible. Photon rate \( \sim 0.01 \gamma/s \).
Summary

- SAFIR will enable very compelling science
- SAFIR is a high priority mission for the astronomical community, for launch in 2015-2020
- GSFC mission concept is ambitious, but technically feasible with modest advances – except for detectors!
- SAFIR is likely to be one of the larger missions driving detector development in the coming decade
- Substantial work needed, especially in the following areas:
  - Large format (10^4 pixel) broadband arrays
  - Very sensitive (few photons noise) detectors