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Cryogenic detectors for infrared astronomy: the Single Aperture Far-InfraRed (SAFIR) observatory

Dominic J. Benford & S. Harvey Moseley*

NASA / GSFC, Infrared Astrophysics, Code 685, Greenbelt, MD 20771, USA

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Abstract

The development of a large, far-infrared telescope in space has taken on a new urgency with breakthroughs in detector technology and recognition of the fundamental importance of the far-infrared spectral region to questions ranging from cosmology to our own Solar System. The Single Aperture Far-InfraRed (SAFIR) Observatory is 10m-class far-infrared observatory that would begin development later in this decade to meet these needs. SAFIR's science goals are driven by the fact that youngest stages of almost all phenomena in the universe are shrouded in absorption by and emission from cool dust that emits strongly in the far-infrared, 20 microns - 1 mm. Its operating temperature (4 K) and instrument complement would be optimized to reach the natural sky confusion limit in the far-infrared with diffraction-limited peformance down to at least the atmospheric cutoff at 40 microns. This would provide a point source sensitivity improvement of several orders of magnitude over that of SIRTF. In order to achieve this, large arrays of detectors with NEPs ranging from a few to a hundred zeptowatts/sqrt(Hz) are needed. Very low temperature superconducting transition edge sensors and far-infrared "photon counting" detectors are critical technologies requiring development for the SAFIR mission.

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1. Introduction

Far-infrared (30μm – 300 μm) and submillimeter (300μm – 1000μm) astronomy are two of the most recent windows to the Universe to be opened, due to the high opacity of the Earth's atmosphere at these wavelengths and the difficulty of detector technology for such low-energy photons. The field of far-infrared astronomy began in earnest in the late 60's and 70's with balloon, aircraft, and sounding rocket

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 ; e-mail: author@institute.xxx .

explorations of the astronomical sky. Examples of such early missions include NASA's Kuiper Airborne Observatory (a 0.9-m telescope operating at low airborne altitudes), the IRAS all-sky survey (a 57cm liquid-helium cooled telescope). With these, the wealth of astrophysical phenomena observable – sometimes uniquely – in the far-IR became apparent. Since that time, though, only modest improvements in sensitivity and angular resolution have been achieved, with ESA's Infrared Space Observatory (ISO), an IRAS-scale telescope with greatly improved detectors.

During this decade, IR space astronomy will be revolutionized by the commissioning of three new observatory-class far-IR to submillimeter facilities: SIRTF, SOFIA, and the Herschel Space Observatory. Each of these will provide substantial improvements in sensitivity and/or angular resolution, although all are also far from the current state-of-the-art in combined aperture and sensitivity for different reasons (SIRTF is limited by aperture; SOFIA and Herschel by photon backgrounds). While SIRTF will probe the faintest and most distant sources in the universe, SOFIA and Herschel will view the brighter sources with higher spatial resolution.

The Single Aperture Far-InfraRed (SAFIR) Observatory has been recommended by the community consensus in the National Academy of Sciences Astronomy Decadal Review [1] as a high priority scientific and technical successor to JWST and SIRTF. SAFIR is envisioned as a 10m-class far-infrared observatory that would begin full-scale development late in this decade, for launch in 2017. This recommendation recognizes the exciting science opportunities offered by the promise of a dramatic increase in sensitivity and angular resolution of a facility like SAFIR in the far-infrared spectral region. SAFIR "will enable the study of galaxy formation and the earliest stage of star formation by revealing regions too enshrouded by dust to be studied by JWST, and too warm to be studied effectively with ALMA.[1]"

2. Scientific Motivation for SAFIR

SAFIR's science goals [2] are driven by the fact that youngest stages of almost all phenomena in the universe are shrouded in absorption by and emission from cool dust and gas that emits strongly in the far-IR, from 20 μm – 1 mm. The continuum emission is due to the incredible efficiency of interstellar dust in absorbing visible and ultraviolet photons and reemitting their energy. The appearance of the early Universe, of active galactic nuclei (AGN) and starbursting galaxies, and of star forming regions is transformed through suppression of the visible and ultraviolet and augmentation of the far-IR and submillimeter. Low-lying far-IR fine structure lines are the major coolants for interstellar gas. Molecular transitions in this spectral range carry the signature of conditions in warm and dense interstellar clouds where stars and their solar systems form. Thus, we must look in the far-IR and submillimeter for clues to the underlying processes shaping the origin, structure, and evolution of our Universe. We need large, cold telescopes to reveal faint, distant sources near the edge of the observable universe, and to show us the details of even nearby warm sources with clarity that matches our capabilities for seeing hotter material.

The earliest stages of star formation, when gas and dust clouds are collapsing and the beginnings of a central star are taking shape, can only be observed in the far-IR. Likewise, the cool dust that will eventually form planetary systems, as well as the cool debris dust clouds that indicate the likelihood of planetary sized bodies around more developed stars can only be observed at wavelengths longward of 20μm (Figure 1).

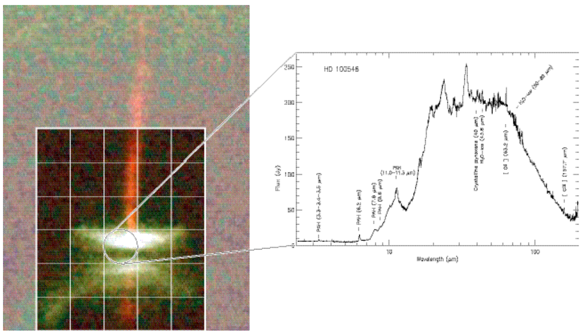

Figure 1. SAFIR imaging spectroscopy of a debris disk.

The most active galaxies in the universe appear to be those whose gaseous disks are interacting in violent collisions (Figure 2). The details of these galaxies, including the central black holes that probably exist in most of them, are obscured to shorter wavelength optical and ultraviolet observatories by the large amounts of dust in their interstellar media. Early stages of galaxy formation appear to result in powerful sub-mm emission indicative of substantial metal enrichment early in the history of the universe. Finally, the warm gas of newly collapsing, unenriched galaxies should reveal itself in hydrogen emission at these long wavelengths. The combination of strong dust emission and large redshift (1<z<5) of these galaxies means that they can only be studied in the far-IR and submillimeter, where SAFIR will provide the sensitivity and angular resolution to peform imaging and spectroscopic studies of individual galaxies in the early universe.

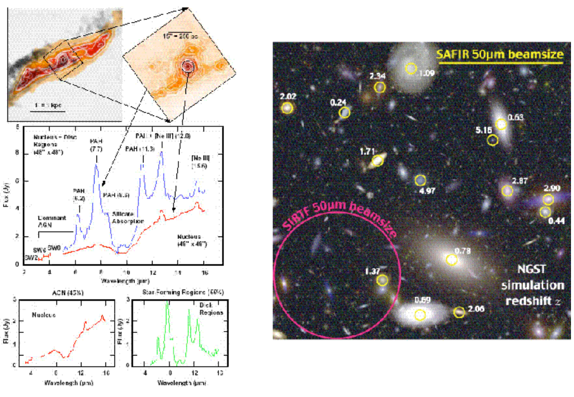

Figure 2. SAFIR's application to AGNs & galaxy surveys

3. Mission Concepts

SAFIR is best thought of as a set of science goals to be accomplished with a variety of observations made in the far-infrared. To insert a single mission picture in place of this more general idea is premature at this time. Studies of SAFIR implementations are underway at NASA/GSFC [3] and NASA/JPL. Several of the ideas are shown below in Figure 3.

The most pressing architectural design requirement is the need to provide a mirror of ~10m size cooled to 4K, to reduce the photon background of the telescope itself. This has proven to be an issue that merits close attention, but one that can be solved. A solution for JWST-like designs is illustrated below in Figure 4; a combination of passive cooling and multistage active cryocoolers is required to maintain the 4K telescope/instrument.

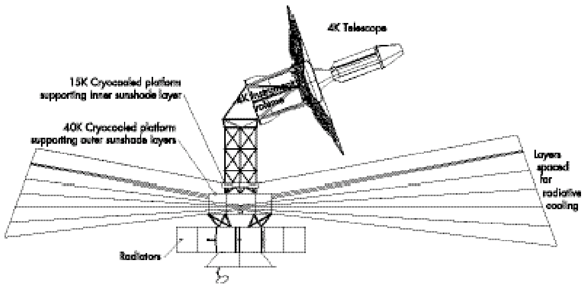

Figure 4. SAFIR cooling concept (JWST-based design, NASA/GSFC) showing the combined passive and active cooling systems required to produce a 4K telescope and instrument bay.

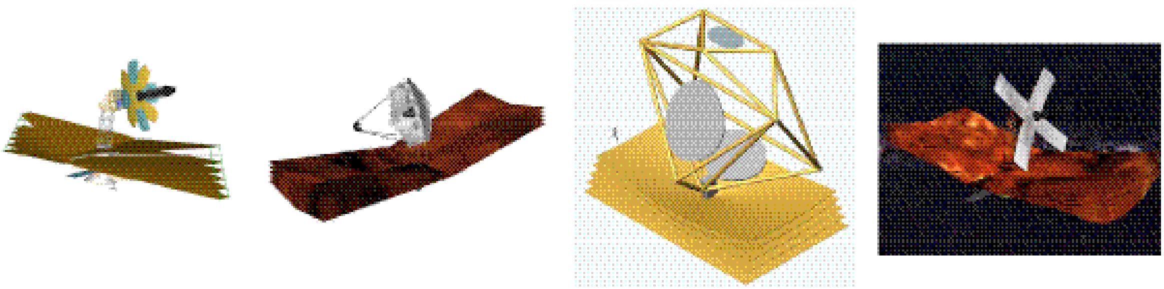

Figure 3. SAFIR mission concepts; [L-R] NGST Strawman design (NASA/GSFC); JWST based design (NASA/GSFC); DART membrane mirror design (NASA/JPL); deployed long-baseline strip mirror design (NASA/GSFC).

4. Detector Requirements

The natural sky background for a cold telescope in space is extremely low as compared to the background from a warm telescope or beneath the Earth's atmosphere. Therefore, detectors that provide photon-noise-limited behavior will be substantially more sensitive than those produced for earlier generations of far-IR astronomy [4]. Based on calculated backgrounds, we estimate the required detector noise equivalent power (NEP) and noise equivalent flux density (NEFD) for a SAFIR camera (Figure 5) and spectrometer (Figure 6).

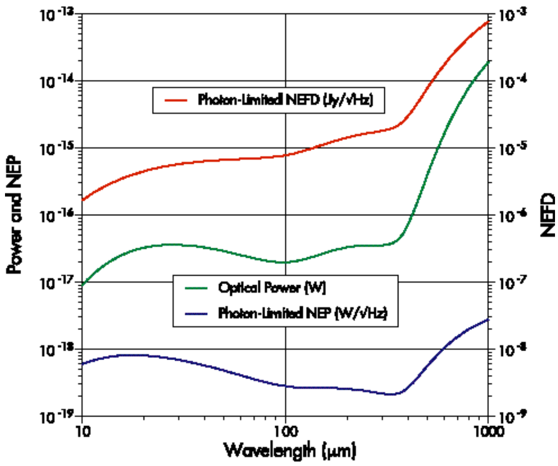

Figure 5. Power, NEP, and NEFD for a camera ($\lambda/\Delta\lambda$=5).

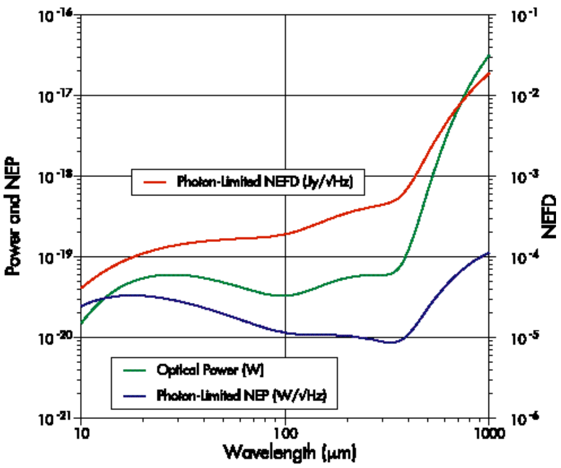

Figure 6. Power, NEP, and NEFD for a spectrometer ($\lambda/\Delta\lambda$=1000).

The camera requires 10^4 pixels of detectors with NEP of 10^{-19} W/√Hz; a $\lambda/\Delta\lambda$=1000 spectrometer requires perhaps 10^3 pixels of detectors with NEP of ~$3\cdot10^{-21}$ W/√Hz. Given current bolometer array performance [5], evolutionary changes to present technology may well be able to produce the camera detectors. The spectrometer detectors are substantially more sensitive, and require near-photon-counting capability.

5. Conclusion

The astronomical community has recommended a large, sensitive far-IR observatory, based on the exciting science opportunities offered by the dramatic increase in sensitivity and angular resolution of a large, cryogenically cooled observatory facility in the far-infrared spectral region. We have developed a conceptual design for SAFIR based on JWST, which includes several instruments requiring arrays of detectors more sensitive than presently available. While present technology might be adapted to a camera, detectors for a spectrometer may require novel technologies.

Acknowledgments

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